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Development of the Moon

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1. INTRODUCTION

This book focuses largely on new results from recent missions and on their implications for how we interpret results from older missions. The new results have also renewed awareness of the Moon as a future target for exploration and many people see development of the Moon, particularly its resources, as a key step in the future exploration of the solar system (Aldridge et al. 2004). The interpretation of the lunar data sets in the context of future exploration and development of the Moon is, therefore, parallel to new scientific interpretations. This is in a sense a forward-looking view inspired in part by New Views of the Moon perspectives. It is also timely, as the United States is currently reconsidering its space exploration program, with a greater focus on renewed exploration of the Moon.

Earth's Moon can be looked upon as an enormous Earth-orbiting Space Station, a natural satellite outside of Earth's gravity well, with raw materials that can be put to practical use as humanity expands outward into the Universe. As outlined in previous chapters, new remote-sensing data for the Moon have reinvigorated lunar science and improved understanding of the Moon's composition, the ages of its prominent formative events, and the character of the earliest lunar crust and its subsequent geologic evolution. In this chapter, we consider how we might use lunar materials for exploration, utilization, and development of the Moon. The Moon offers a nearby location from which to develop resources and capabilities to explore further in the Solar System. The natural resources of the Moon include minerals, rocks, and soils, which can be processed to produce metals, oxygen, glass, ceramics, and other useful products (McKay et al. 1992). Water ice may exist near the poles and low concentrations of volatiles deposited by solar wind (H, He, C, N) are trapped in the regolith. A low gravity field, limited atmosphere, and a location in space near the Earth provide an environment in which

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resource development is challenging, but possible, with products that are useful in space or, in limited cases, on Earth. Proper utilization of these resources, in the establishment of lunar habitations and as fuel for planetary exploration, will provide an invaluable stepping-stone for humanity as it grows beyond the limits of Earth and of our Solar System. Near term uses of these resources can have economic implications in space industrialization and opening up virtually unlimited sources of energy for a growing world economy. Scientific and economic considerations must be melded into plans for future lunar exploration and development, and commercial interests can be expected to join the scientific and technical objectives that have formed the basis for previous lunar exploration programs.

This chapter addresses the major topics that must be considered in developing a strategy for the exploration and development of the Moon:

- ***Why go to the Moon?*** The objectives of lunar exploration will be based on human society's need for more information, energy, and raw materials that constitute the principal underpinnings of economic growth. The chief themes addressed here are the expansion of humans into space, space industrialization (possibly including tourism), space transportation, the search for more energy, the Moon as a laboratory for planetary science, and astronomy and other science on the Moon.
- ***Getting There and Back***. Although the Moon is near enough to Earth to be considered part of an economic system with Earth, routine and safe transportation within the Earth-Moon system will need to be developed.
- ***Lunar Material Resources***. The resources of the Moon are known in a preliminary sense, but further exploration for resources and the determination of their practical economic utility will be required. The scale of resource development on the Moon may be small by terrestrial standards, but for applications in space, production of relatively small amounts of materials (e.g., propellants) from the Moon may be economically feasible because transportation costs can be much smaller from the Moon than from the Earth.
- ***The Lunar Environment.*** In developing the Moon, attention must be paid to the preservation of the environmental characteristics of the Moon that are unique or those that form the basis for its beneficial utilization. Large-scale economic activities on the Moon could locally modify the lunar atmosphere, possibly interfere with uses such as astronomy, or produce visible effects that some might consider undesirable.
- ***Humans on the Moon***. Human outposts and settlements on the Moon appear to be feasible, but will have to operate under a variety of economic and environmental constraints, if they are to be viable in the long term.
- ***A strategy for lunar exploration and development***. A strategy is advanced as a baseline from which to consider alternative approaches and prioritize investments in science and technology.

The strategic exploration and development of the Moon are greatly facilitated by previous and ongoing analyses of sample and remote sensing data from the Apollo and Luna missions, Earth-based telescopic data for the Moon, lunar meteorites, and from the more recent Galileo, Clementine and Lunar Prospector missions. It is anticipated that the gathering of more scientific information will continue to be critical to the identification of opportunities for, and constraints on, lunar development. Currently, the European Space Agency (ESA) is conducting the SMART-1 mission to the Moon. Japan, India and China are developing or planning lunar missions. Recently, NASA has been directed to develop plans for a renewed human exploration program beyond low Earth orbit, with robotic missions to the Moon starting in 2008 and human missions beginning in 2015-2020.

2. WHY GO TO THE MOON? EXPLORATION RATIONALES AND MOTIVATIONS

Past exploration of the Moon has been driven by political forces (e.g., Apollo, Luna missions) or by science and technology (e.g., Galileo, Clementine, Lunar Prospector, ESA, and Japanese missions). The impetus for missions being planned by India and China may be driven in part by a desire to demonstrate technological innovation. Future lunar exploration may be driven by economic or strategic purposes. What is our current motivation for further exploration and possible utilization of the Moon? Here we identify six themes as those that are most likely to guide the strategic exploration and utilization of the Moon in future years.

2.1. Expansion of humans into space

Humanity has evolved to occupy nearly every available niche on Earth. This evolution is a result of the inherent need to survive and prosper that is a fundamental drive of living organisms. There is no reason to believe that this drive will cease at the edge of space. Some would argue that the movement of humans to the planets and out of the Solar System is a basic survival strategy for the species, because of the potential for disastrous natural and human-caused events on a single planet (Gott 1993).

Constraints to the expansion of humans beyond Earth are primarily technological and economic, but health and safety of crewmembers also is a major concern. Space travel for humans, using existing chemical propulsion systems, is limited to the Earth-Moon system, Venus and Mars, because travel times become much longer when traveling beyond the nearest planets. Advanced propulsion systems (solar and nuclear electric, nuclear thermal, nuclear fusion) are being studied that might reduce the one-way transportation time for Mars (Carlson 2003; Frisbee 2003; Head et al. 2003). Human missions beyond Mars are unlikely for the next 30 to 50 years.

Human health and performance is a principal concern in human missions that remain away from Earth for extended periods of time. Our experience base is deficient for Mars exploration, in which a trip of several months in weightlessness is followed by a surface stay that may either be short (30 to 90 days) or long (~500 days), followed by a several month long return trip to Earth. Russian cosmonauts spent more than 1 year in weightlessness, which is approximately the time that would be spent in space in a human mission to Mars (e.g., six months of weightlessness each way). But three days is the longest period of human experience in a low gravity planetary surface environment by an Apollo astronaut. It is known that humans adapt to weightlessness in ways that are often detrimental to the human body when they return to the Earth's gravitational field. Exercise and medication are to some extent effective countermeasures. Astronauts who exercise vigorously while in space appear to readapt to the Earth's gravity field quite rapidly (D. R. Pettit, pers. comm.). A lunar outpost program must include a program to establish the limitations of the human body for long stays on the Moon and readaptation when returning to Earth. These data will be applicable to the human exploration of Mars.

Operational strategies are also important for long-duration missions. The balance between autonomy of crews on a planet's surface and the support that they receive from the Earth will change markedly with the distance of the planet from the Earth. For the Moon, communication is slightly delayed (a few seconds); however in Mars missions, the round trip light time may be 16 to 30 minutes, depending on the relative location of Mars and Earth. This increases the crew's need for autonomous operation in periods of emergency. A lunar outpost can provide a realistic environment for testing operational approaches for humans and robots supported by mission controllers on Earth, with growing autonomy over time.

It would be foolish for humans to plan to stay in space or on planetary surfaces for several years or longer without producing food. Plants are essential for food and also for long-term stable life-support systems, as they can recycle H_2O and CO_2. Cultivation of plants for food can provide a basic diet for astronauts as well as psychological benefits for people living for years in cramped quarters. The Moon can provide a laboratory for testing the viability of plants and animals in the space environment and the possibility of plant nutrients from indigenous materials (Henninger and Ming 1989).

Spacecraft systems need to be tested for time periods that are consistent with the times required for human missions to Mars. For voyages lasting many years (2.5 to 3 years for a human mission to Mars), testing over equivalent or longer periods of time is needed in relevant environments. The Moon may provide a "test bed," a facility where technologies that are intended for use on planetary surfaces may be tested. A lunar test bed could eventually grow into a sophisticated activity, including the capability to maintain, repair and improve these technologies. Technologies that might be useful for Mars exploration that could be developed and tested on the Moon are shown in Table 6.1.

The Moon is an ideal place to establish a technology test-bed facility because it is much closer to Earth than Mars, which can allow easier recovery from accidents or anomalous conditions, while providing relevant environmental conditions for the crew and hardware.

Table 6.1. Systems technology test beds at a lunar outpost.

Mars Application	***Lunar Demonstration***	***Comments***
Highly reusable EVA suits	Long term performance in representative environment: -Operational tests of agility -Long duration operations -Multiple uses -Maintenance and repair	A suit designed for lunar gravity may not be useful on Mars, due to its higher gravity. However, a suit designed to meet Mars requirements should be fully testable on the Moon
Long range tele-operated rover	Operated from Earth to simulate crew operations on Mars	Communication delay times of a few seconds may also be realistic for Mars in the case that astronauts operate the equipment from a Martian outpost.
Closed life support systems	Long term operation in representative environment, including maintenance and repair	1/6 g may cause more severe effects than on Mars. Therefore, a system designed for the Moon should be applicable for Mars.
Nuclear reactor power system	Robotic emplacement, shielding using indigenous materials; monitoring of radiation environment with robotic systems.	The design and operation of a nuclear power system should be very similar for both Moon and Mars, though the Martian atmosphere will need to be considered in terms of its effects on system design.
In-situ resource utilization	Subsystems, long-duration operations: -Electrolyzers -Liquefaction of cryogens -Fluid transfer -Storage	Detailed extraction processes will not be the same, but the components will be similar.
Human health and performance	Long-duration tests at 1/6-g with many subjects.	More severe environment than Mars; if humans can flourish on the Moon, they will be able to adapt to Mars.

It should also be possible to create a robust testing capability on the Moon with flexibility to change if new and better technologies or operational protocols are developed. A routine transportation system to the Moon would be required to support such a test-bed facility. Eckart (1999) has provided a thorough examination of the technical issues associated with establishment of lunar bases.

2.2. The search for energy alternatives

Resources on the Moon, especially solar energy or ^{3}He, could provide new sources of energy for Earth. Continued economic prosperity of the Earth is a strong function of the availability of inexpensive energy (e.g., Criswell 1994; Schmitt 1997). The current energy use of the developed nations of the world is approximately 6 kWt (kilowatts of thermal energy) of continuous power per person, but much of the world survives on far less. Most of the world's energy is provided by the combustion of fossil biomass (especially coal and oil). Global demand for energy will likely increase by a factor of at least eight by the mid-point of the 21st Century due to a combination of population increase, new energy intensive technologies, and aspirations for improved standards of living in the less-developed world (NRC 2001). If the Earth's population increases to 10 billion people and all people of Earth are provided with electricity at the current average in the developed world (2 kWe/person (kilowatts of electrical energy), 20 billion kWe (20,000 GWe) of energy production would be required. At this level of power, known and predicted sources of fossil fuel would soon be consumed. Because so much more energy is required than is now produced, the energy sources should also be cleaner. Two sources of abundant clean energy have been identified as potentially capable of filling that need—space solar power and nuclear fusion. The Moon could play a substantial role in the development of either.

2.2.1. Solar Power Satellites. The concept of Solar Power Satellite (SPS) systems located in geostationary Earth orbit (GEO) was formulated by Glaser (1968). In his concept, large arrays would be assembled in GEO and located above the cities or regions that needed power (Fig. 6.1, after Mankins 2001a). The arrays could be hundreds of square kilometers in dimension. Typical designs for these arrays have yielded masses of 50,000 metric tons (mt) of material for

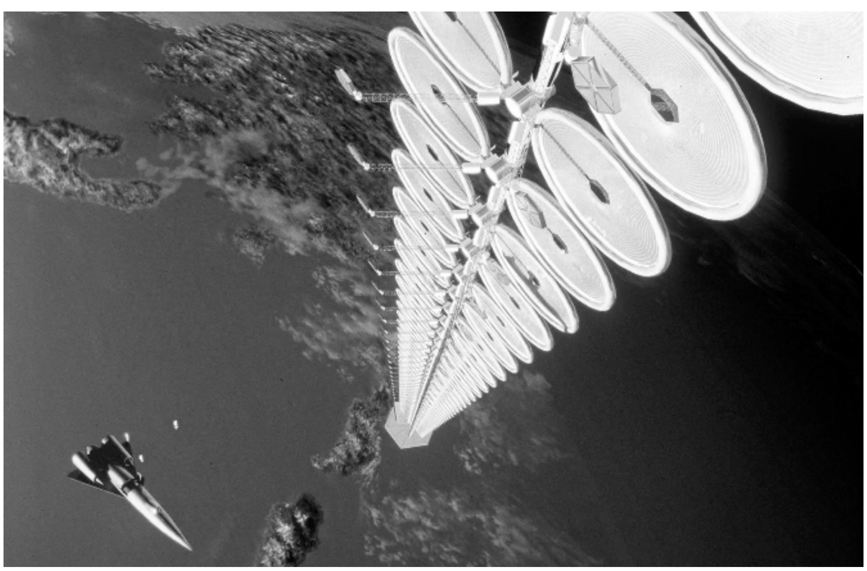

Figure 6.1. Solar Power Satellite: A recent concept (after Mankins 2001a) in medium or low Earth orbit.

each 2GW of power capability. Recent advances in technology (Grey 2001; Mankins 2001a,b) have somewhat reduced the estimated mass and improved the estimated performance of these systems, but the high cost of Earth-to-orbit transportation is the overwhelming barrier to the deployment of the system. If the cost of transportation from Earth to Low Earth Orbit (LEO) can be lowered to $400/kg (a factor of 25 lower than current costs), recent studies (Mankins 1995) indicate that the cost of energy can be lowered to about $0.05/kWh, but it will be difficult for SPS to compete with energy from fossil fuels for the next 20 years or more (Greenberg 2000).

As noted by DuBose (1985), essentially all of the materials needed to construct solar energy collection, conversion, and power-beaming facilities in space or on the Moon are available from lunar materials (Table 6.2). Recent research has suggested that silicon solar photovoltaic (PV) devices can be produced from lunar materials with an investment in hardware shipped from Earth that is quite small in comparison to the amount of energy that can be produced (Ignatiev et al. 1998).

Bock (1979) modeled the deployment of a SPS system using lunar materials, and using processing approaches studied by Criswell (1978) and Miller (1978-1979). The lunar regolith could provide at least 90% of the required materials (a major part of the total mass of the SPS is structure) in the Bock study and 99% in the DuBose (1985) study. The performance of structural elements derived from the Moon would probably be lower than those brought from Earth, so the mass of the DuBose SPS was about 10% greater than required for the same system constructed entirely from terrestrial materials. Transportation will remain a principal hurdle. The Bock (1979) study envisioned using an electromagnetic launching system (mass driver) capable of very low $/kg launch costs from the Moon (Billingham and Gilbreath 1979). A mass driver efficiently converts electrical to kinetic energy using a linear motor concept. If the cost of power on the Moon were as low as that on Earth, transportation costs from the Moon could be very low. However, such a launch system would require significant engineering development and its cost is currently unknown.

In general, the economic viability of lunar resources depends on a tradeoff between the cost of developing lunar manufacturing systems and the cost of transportation to space. If lunar processing systems can be designed that produce large quantities of materials in their useful lifetime, even though the development cost is high, the cost of production spread against the amount

Table 6.2. Solar Power Satellite elements and materials (from DuBose 1985).

Functional Element	***% of system***	***Principal materials***	***% available on Moon***
Silicon photovoltaic arrays	45		
- Cell covers and substrates		Fused silica	100
- Solar cells		Silicon	>99.99
- Interconnects, support wires, connectors, tensioning system		Aluminum	100
Structure	14	Aluminum	100
Power Management, Distribution	6.5	Aluminum	100
- Electrical conductor buses		Aluminum, fused silica	90
- Switches, energy storage		(flywheel), silver, copper	
Microwave transmitters (klystron amplifiers, waveguides)	33	Aluminum, titanium, steel (with Co, V), tungsten, copper, carbon, silica, etc.	98
Miscellaneous other	1.5	Various	96

of material produced can be reasonable. The cost of transportation from the Moon to space can become far smaller than the cost of transportation from Earth, because the Moon's gravitational field is smaller and complications of the Earth's atmosphere are eliminated (see Section 4.5).

2.2.2. Lunar Power System. A Lunar Power System (LPS) is similar in principal to the SPS, but consists of large PV arrays at both limbs of the Moon beaming energy to Earth by microwaves (Fig. 6.2). This system could be built the lunar surface of materials available on the Moon (Criswell and Waldron 1990). In the Criswell and Waldron (1990) concept, solar energy is collected by photovoltaic cells deposited directly onto the lunar surface. The electricity is conducted to a microwave transmitter that beams microwaves onto a reflector aimed at Earth. A complete system includes many of these assemblages that complete a filled aperture as viewed from Earth. Although the distance to Earth is much greater than that from GEO, the focusing effect of the large lunar array can be efficient in transmitting power to Earth. The machinery required for production of solar arrays on the Moon is small in mass compared to the energy collected and transmitted to Earth. Transportation costs are minimized compared to those required for installing a SPS in Earth orbit.

The micrometeorite and radiation environments of space and the lunar surface will cause slow degradation of photovoltaic arrays. In space, if high efficiency cells are used, this

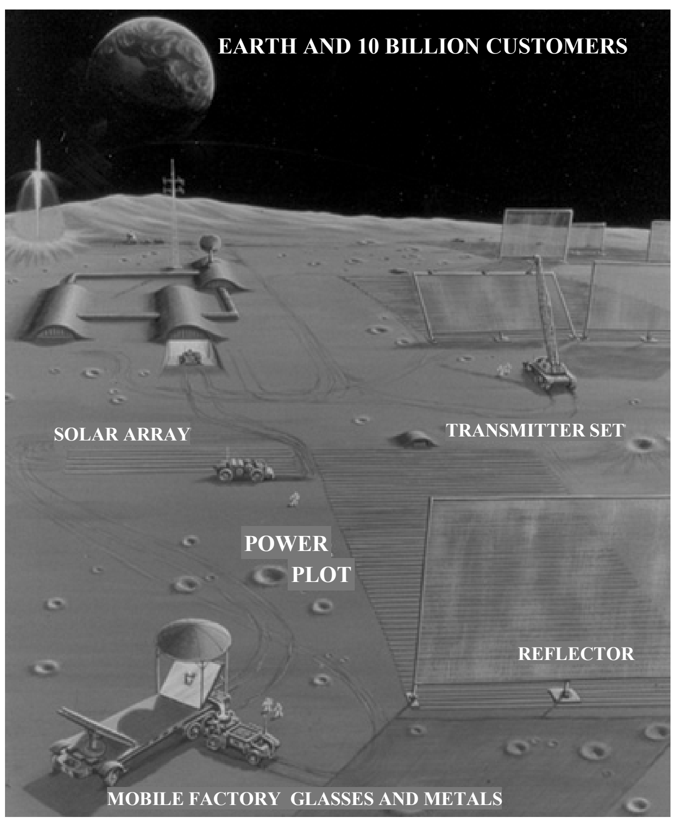

Figure 6.2. Power plots within a demonstration lunar power base (© David R. Criswell 2002). The power plots are areas of solar cells, connected to transmitters that beam microwaves toward the reflector. The full set of reflectors constitutes a filled array as observed from Earth.

degradation can be severe. As a lunar power system would use lower-efficiency solar cells, the radiation degradation is reduced and the replacement of micrometeorite-damaged solar arrays on the Moon by the same process by which they were produced should constitute a minor cost to system operations. Care will be needed to control dust generation near the lunar arrays; however, it is interesting to note that the laser retro-reflectors emplaced on the Moon by Apollo have performed without serious degradation for over 30 years and are still in use (e.g., Williams et al. 2001).

The technologies required for LPS are generally highly advanced (Criswell 1996). The requirement for Moon-to-space transportation of materials (a major factor in an SPS made of lunar material) is substantially reduced. If the machinery for production of solar arrays and beaming hardware can itself be manufactured from lunar materials, the transportation requirement from the Earth can be further reduced. Automation of production and installation equipment reduces the number of people required to operate the lunar production facilities. The transportation of materials from Earth to the Moon is more expensive than taking the same materials to GEO; however, the amount of equipment and materials brought from Earth to the Moon is greatly reduced, and the time required for construction should also be decreased. The availability of lunar propellant and propellant depots in lunar orbit or at an Earth-Moon Lagrangian point such as L-1 can reduce the transportation costs from Earth and Moon.

The principal materials that are required for constructing the LPS are similar to those listed in Table 6.2 for a SPS constructed in space from lunar materials, with the exception of the supporting structure for the silicon PV arrays, which is provided by the lunar surface in the Criswell and Waldron (1990) concept.

If an LPS can be constructed on the Moon, it follows that power on the Moon could be very inexpensive (perhaps a factor of 10 less than the cost of the beamed power on Earth) because the requirements for beaming and receiving the energy would be eliminated. Criswell and Thompson (1996) predict very low energy costs on Earth (<$.01/kWh) with a fully developed LPS. No analysis has been made of the economic implications of essentially free power on the Moon but some speculation is possible. The energy to transport a kilogram of material from the Moon to space (including to the Earth) is less than 1 kWh. If the cost of electricity on the Moon were $0.01/kWh, the energy cost of transportation from the Moon to Earth, for example by an electromagnetic launch system, could become vanishingly small. Additionally, as most resource processing is energy intensive, low cost lunar power can also lower the cost of commodities produced on the Moon.

2.2.3. ^{3}He. The Moon also might also play a role in the development of nuclear fusion as a long-term source of power on Earth (Kulcinski et al. 1989). The Moon's surface is covered with many meters of regolith that stores low but ubiquitous concentrations of Helium-3 (^{3}He), an isotope of helium that undergoes fusion reactions with deuterium (D-^{3}He) and with itself (^{3}He-^{3}He), which may ultimately be tapped for energy. The atom ^{3}He is quite rare on Earth, but has been implanted into the surface of the particles of the regolith covering the Moon. Concentrations are very low (8-10 ppb in maria) (Taylor 1993, 1994) so about 21 km^2 of regolith would have to be mined to a depth of 3 m to extract one metric tonne (mt), if the bulk density of lunar soil is 1.6. However, the energy content of ^{3}He is very high, so very little would have to be transported from Earth in proportion to the electricity production requirements. The energy equivalent value of ^{3}He relative to $7 per barrel crude oil is $1 billion per mt; 40 mt of ^{3}He could provide current U.S. energy needs for a year (Kulcinski and Schmitt 1992). There is estimated to be about 1 million mt of ^{3}He in the upper 3m of the entire Moon (Taylor and Kulcinski 1999) and the Tranquillitatis Ti-rich lunar mare alone is estimated to contain at least 10,000 tonnes of ^{3}He (Cameron 1993). By-products of lunar ^{3}He extraction, largely H, O, N, C, and H_2O, have large potential markets in space and would add to the economic attractiveness of this business opportunity.

A concept for a lunar volatiles miner and processor was developed by Sviatoslavsky (1992). This system would mine its way through the lunar regolith on normally parallel linear tracks, avoiding craters and boulder fields that are beyond the capabilities of the bucket wheel excavation system. Coarse material would be separated from relatively fine material (about 50-60% of the regolith) and discarded or saved for later use as construction aggregate. The fine material would be heated in the processor to 700–800 °C (avoiding the decomposition of troilite, FeS) to extract 80–90% of the solar-wind volatiles. The volatiles would be stored temporarily in tanks that would be picked up and taken to a central base refinery for separation of ^3He, H_2 and various other by-products, including water. This miner/processor concept can be used with a "spiral mining" architecture (Schmitt 1992) that transports the extracted volatiles by pipe to a semi-mobile central habitat and refinery that would avoid eventually long distance transport to a central base. There is no doubt that extensive engineering development would be required to create an effective process for extraction of ^3He and transporting it to Earth, but no known technological breakthroughs are required. The most important of these developments would be in the areas of low-maintenance excavation systems, highly effective thermal-extraction systems and the large power sources that would be necessary for heating.

Environmental questions related to lunar ^3He mining have not been completely addressed. Vondrak (1989) concluded that human activities at a modest lunar outpost could easily add more to the lunar atmosphere than natural processes (principally from the solar wind), but the effects should be localized as gases are removed rapidly. For larger activities, current understanding of the lunar environment is insufficient to predict where and when the environment could be degraded for other activities. Maintenance of high vacuum conditions for astronomical observations is probably the most demanding requirement. Establishment of major or long-term activities that can generate atmospheric contamination should be preceded by experimental verification of the behavior of the lunar environment.

The current state of fusion energy research is an issue relative to the use of this lunar resource and parallel research in this area would be required. U.S. federal fusion resources have been concentrated on the D-T reaction and not on alternative fuels such as ^3He. No D-T magnetic containment fusion device that produces more energy than it consumes has yet been developed and the containment requirements for D-^3He fusion reaction are more severe than those for the D-T reaction. However, other containment approaches, such as inertial electrostatic confinement (IEC), are being studied. IEC devices may have other applications than large scale electrical power production, including isotope production, mobile power sources for ships and planes, nuclear waste transmutation, and several others (Kulcinski 1996). The development of lunar ^3He could also lead to the development of fusion rocket propulsion systems, with long-term implications for interplanetary missions in terms of reduced trip times, associated reductions in astronaut exposure to the low-gravity and radiation environment of space.

2.3. The industrialization of space

Various types of production facilities might eventually be located in space as profit-making ventures or to relieve environmental pressures on Earth. Most investigations of material processing in space to date have been aimed at producing new and unique materials by taking advantage of the micro-gravity environment. Little research has been aimed at production in space, because the cost of space transportation is so high that only products that sell at prices several times the cost/mass of space transportation can be considered. Currently, the bulk cost of transportation from Earth to orbit is approximately \$10,000/kg or \$10/g, so any product returned from space must carry a price far above that of gold (~\$10/g) and probably several times that much (depending on manufacturing costs), unless launch costs are reduced.

The Commercial Space Transportation Study (CSTS) (Boeing et al. 1994) considered space manufacturing in the context of the current infrastructure available to experimenters.

The CSTS concluded that a space manufacturing facility could be profitable if the cost of Earth to orbit transportation fell to about $1200/kg. Even if transportation costs from Earth reached that level, there would still be few products valuable enough to merit the transportation costs of the raw materials into space.

The CSTS study considered the most likely customers for an initial space industrial park to be microprocessor and medical tissue producers, as well as other industries seeking access to microgravity or high vacuum to improve production processes. Few actual products have been identified; however, possibilities have been identified that will be tested in the International Space Station. For example, it has been discovered that certain porous and inter-metallic ceramic materials that can only be produced in microgravity may allow strong and effective bone replacements (Zhang et al. 1999) that could last the lifetime of the patient, rather than the 10 years typical of current materials. Each of the approximately 10,000 hip replacements made in the U.S. each year might use 1 kg of space-produced materials. The capability of producing the required materials on the Moon and transporting them to an orbital manufacturing facility could be feasible if the total costs were a small fraction of the cost of a hip replacement operation ($10,000). A space business park could require a number of similar applications to be viable.

The development of the infrastructure (transportation, habitats in space, power) for space manufacturing could enable other uses, such as space tourism. Tourists in space would require a large range of supplies and materials, including food, which might be brought from the Moon, if production and transportation costs were low enough. Propellant produced on the Moon would find use at the space industrial park as well as helping to lower transportation costs from the Moon. Aeroshells for spacecraft returning to Earth could be fabricated from lunar materials to lower the cost of returning manufactured products. Some of the products that a lunar outpost might provide to a space industrial park are listed in Table 6.3.

2.4. Exploration and development of the Solar System

The human exploration and development of the inner Solar System is critically dependent on low cost space transportation. Development of the Moon's resources can help to reduce the cost of space transportation. In the near term, humans in space will be limited to trips of a few months to a few years, in rockets that use chemical propulsion, particularly liquid hydrogen

Table 6.3. Potential lunar products for space industrialization and tourism.

Product	***Use in Space***	***Source***
Propellant; H_2/O_2 for life support	Space transportation, station-keeping for orbital assets; life support consumables; energy storage (e.g. fuel cell reactants)	Regolith; ilmenite; polar ice deposits
Raw materials (metals, oxides, ceramics)	Large structural platforms; specialty manufacturing; Earth entry aeroshells	Mare and highland regolith
Organic constituents (e.g. plastics)	Manufactured parts for use in space	Lunar polar volatiles; recycled space industrial wastes
Inorganic reagents (e.g. H_2SO_4)	Chemical processing	Mare regolith; lunar polar volatiles
Solar PV cells	Power systems	Lunar silicon
Food; manufactured goods	Earth orbit tourist facility	Recycled products; Regolith

and oxygen in the Earth's neighborhood, or methane and oxygen for Mars missions. For any mission to high Earth orbits (e.g., GEO) or beyond (Moon, Mars), approximately 75% of the mass that must be lifted from Earth is propellant to take the spacecraft beyond LEO. Thus, an expansion of exploration and utilization in the inner Solar System is propellant intensive. If the cost of propellant delivered to particular points in space from the Moon is less than the cost of delivering that amount of propellant from Earth, propellant production on the Moon can be economically competitive if the total demand is large enough to amortize the cost of installing the production facilities.

For a round trip to the Moon by a team of astronauts, the availability of propellant on the Moon reduces the total mass that must be lifted from Earth to LEO by more than a factor of 2 (Siegfried and Santa 1999). If a high-Earth orbit or lunar orbit refueling depot were to be supplied with propellant from the Moon, another factor of 2 reduction can be obtained, because the propellant required for landing on the Moon no longer would have to be brought from Earth. Thus, the Earth to orbit transportation vehicles could be a factor of four smaller and current space transportation systems, such as the Space Shuttle or large expendable vehicles.

Recent NASA exploration strategies (e.g., NASA 1998) have focused on the use of the Earth-Moon Lagrange (libration) point L-1 as a high-Earth orbit transportation node. The Lagrange points are points of equilibrium in the Earth-Moon and Sun-Earth systems (Fig. 6.3). The Earth–Moon L-1 point provides a convenient location in high Earth orbit with the special property that it is fixed in position with respect to the lunar surface and trips to any place on the Moon from L-1 can be carried out at any time. NASA studies have identified low-energy trajectories between Lagrange points in the Sun–Earth–Moon system (Lo and Ross 2001). Concepts exist for using the L-1 point as a location where large space telescopes could be constructed and then moved farther from the Earth to the Sun–Earth L-2 point.

With fueling both on the lunar surface and an L-1 depot, a single Space Shuttle launch could propel a fully fueled crew module on a three-day trip to the L-1 point, where the crew could transfer to a lunar descent/ascent stage for a one-day trip to the Moon. When they were finished working on the Moon, their descent/ascent stage would have been refueled on the Moon and they would return to L-1, transfer to their crew module and return to Earth. At that point (assuming that lunar propellant is inexpensive to produce and transport), the cost of going to the Moon might be only slightly larger than going to L-1 or GEO.

In a recent Mars reference mission strategy (NASA 1998), an interplanetary vehicle and its H_2/O_2 propellant would be taken from LEO to L-1 using an efficient ion propulsion system. Crews would be transported separately to L-1 in a crew transfer vehicle, which could be left at L-1 for their return to Earth. The H_2/O_2 interplanetary vehicle would be used to take the crew to Mars and return. Availability of propellant from the Moon would reduce the size of the ion

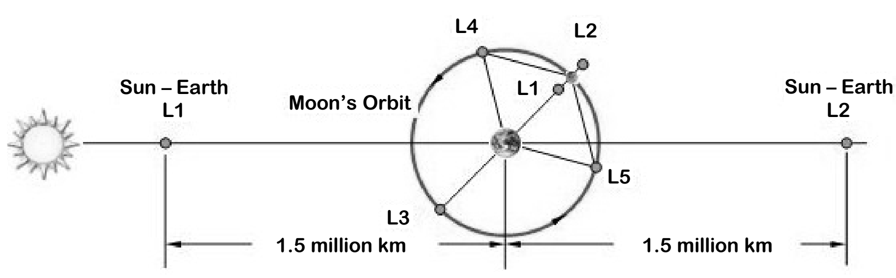

Figure 6.3. Schematic view of Earth–Moon Lagrangian points of gravitational stability in the Sun-Earth and Earth-Moon system.

propulsion system required and could influence the strategy for using the crew transfer vehicle (it might be used for lunar missions while the Mars crew were in transit).

The discovery of hydrogen enhancements on the Moon (Feldman et al. 2000, 2001), probably within permanently shadowed craters, increases the likelihood that propellants can be produced on the Moon. Water concentrations of 1 to 10%, may exist, the total quantities may be on the order of 10^{10} mt, and other useful volatile species may be present. The water could be removed by heating the regolith above ambient temperature (<100 K) and condensing the water vapor. Energy requirements would not be excessive, but development of technology for working within the permanent shadow may be difficult (Duke et al. 1998).

It is also possible to extract hydrogen or produce water from typical lunar regolith, where it exists in 50–100 ppm concentrations, by heating of the regolith to ~800 °C (Gibson and Johnson 1971). A concept for extraction was developed by Eagle Engineering (1988) and has been updated by Diaz et al. (2004). A large quantity of regolith must be mined and heated, so excavation, hauling, and extraction processes need to be very efficient in terms of their hardware mass, to avoid large transportation costs for the equipment. The economic extraction of hydrogen from the regolith depends highly on the cost of energy on the Moon, because of the energy required for heating. If energy becomes inexpensive on the Moon, it may become feasible to extract hydrogen in equatorial regions of the Moon. In addition, the carbon and nitrogen by-products of heating the regolith could be used for human support. These constituents also could be valuable byproducts of ^3He production (Schmitt 1997).

Abundant and relatively inexpensive water in space would find a variety of uses other than propellant, including life support and chemical processing, which might otherwise be shunned because of the cost of replacing water lost from the system during processing. Water also can provide an effective radiation shield for space habitats in which crews must spend extended times. Propellant production on the Moon would probably be the initial development step, because its availability reduces the launch masses required from Earth for many purposes. Production of a wide variety of materials that may be useful for space industrialization and exploration could follow. Materials ranging from simple uses of lunar regolith for shielding of space assets (McKay et al. 1992) to production of photovoltaic cells (Ignatiev et al. 1998) have been suggested. Thus, the development of lunar resources, first for transportation and, later, for construction, infrastructure development, and support of humans can pave the way for human expansion throughout the inner Solar System.

2.5. The Moon as a planetary science laboratory

The Moon provides a natural platform for its own study and for the study of planetary processes, particularly volcanism, crustal evolution and impact. The importance of lunar science and what the Moon can reveal about Solar System and planetary history is the subject of much of the preceding chapters in this book. This section addresses only those aspects of lunar science that would be enabled by the development of the Moon and much easier access to the Moon by humans. Problems that might be addressed if a lunar outpost were established include:

- ***Highland lithologies and the history of the lunar crust.*** Because the impact flux prior to 4.0 Ga ago was much higher, the Moon is believed to have a "megaregolith" of fragmental material, perhaps several kilometers in thickness. In the megaregolith a wide variety of ancient crustal rocks may be found. The capability to recognize and extract the range of rock fragments it contains, describe them, and subject them to detailed analysis would benefit from an on-site ability to collect and process materials, to recognize minor constituents of the regolith and perhaps, to do much of the analysis on the Moon.
- ***Mare filling history***. The near-side maria were emplaced within basins excavated by impacts prior to about 3.9 Ga ago. The history of this process probably was complex,

consisting of periods of volcanic activity interspersed with periods of quiet, in which impacts modified the surface. A sequence of volcanic and regolith units may be encountered with depth. Drilling to depths of 1-2 km at various locations within the mare could provide the history of this process and an understanding of the time scale, source of material, and nature of the external environment as it existed during the basin-filling period. This is more likely to be accomplished when the Moon is readily accessible to humans.

- ***Magnetic history of the Moon.*** The nature and history of a lunar core might be understood if the Moon had an internally generated magnetic field, as believed by some to have been the case in the period around 4 Ga ago (e.g., Runcorn 1996). Oriented samples from successive layers of mare basalt in an older mare could both provide specimens could provide a definitive test of the existence, magnitude, and orientation of a lunar magnetic field between about 3.7 and 4.0 Ga ago. This is more likely to be accomplished if humans are present on the Moon.
- ***Lunar resources.*** Exploration for uncommon lunar resources may require a large number of samples to be collected over a large area. Because the regolith is highly mixed, studies might begin with the identification of a particular rock composition among regolith fragments and proceed to establishing the concentration of those fragments over an extended area. By studying large numbers of samples, the point of origin of the fragments could be defined, leading to more intensive exploration by drilling or other sampling methods. A systematic campaign of this type for economic reasons would also yield unique scientific data.

Although significant exploration objectives remain to be carried out from orbit, most future work will require detailed observations on the surface. The presence of humans working on the Moon opens the possibility for a permanent geoscience laboratory, which can contribute to making lunar exploration efficient as well as introduce new science capabilities. A geoscience laboratory on the Moon could undertake a range of investigations: exploring the features of the Moon to determine their composition, age, and role in the formative history of the Moon; and conducting experimental and observational investigations into the processes by which these features were produced. The research facilities that have been established by many nations in Antarctica can provide a useful model. The capabilities of such a laboratory could include:

- ***Exploration vehicles***. Such vehicles would greatly enhance exploration and detailed study, as well as emplacement and maintenance of instruments, on a global basis.
- ***An analytical laboratory.*** This would be capable of conducting very sophisticated geochemical, biochemical and isotopic analysis of samples (Zumwalt 1997). This could also be an instrument development laboratory, focusing on instruments such as very high-resolution mass spectrometers, taking advantage of the vacuum environment of the Moon's surface.
- ***An experimental laboratory.*** This would allow properties of lunar materials to be tested under a variety of pressure and temperature regimes. This could include an active experimental capability for studying lunar atmospheric phenomena and the lunar environment.
- ***Subsurface access capability***. It may be feasible to conduct drilling or tunneling operations to depths of up to 10 km in the Moon, as temperatures remain moderate. At these depths, the base of lunar maria and the subsurface structures around major impact basins could be investigated.
- ***Cryogenic laboratory.*** Near the lunar poles where access to permanent shadow is possible, large volume cryogenic laboratory facilities allowing the study of natural materials at temperatures associated with the outer Solar System should be feasible.

- ***Curatorial facility.*** Samples collected for study from all over the Moon would be stored in this facility for subsequent investigations on the Moon and for transfer to study on Earth. The facility would have the capability of storing rocks, regolith samples and cores in controlled ambient lunar conditions. Relatively large samples could be maintained in the facility, as the sample collection trips to particular locations on the Moon may be infrequent.
- ***Equipment maintenance and repair facility.*** This facility would be a well-equipped machine shop, capable of manufacturing replacement parts, including circuit boards, for facility equipment. This facility might double as an experimental facility for fabrication processes utilizing indigenous feedstocks.

2.6. Astronomical observatories on the Moon

The Moon may provide a particularly useful platform for large astronomical instruments (Mumma and Smith 1990). On the Moon, an optical telescope can function in the same manner as a terrestrial telescope, which would allow it to be rapidly and accurately pointed at a target in the sky. There is no atmosphere, and therefore no atmospheric disturbances at optical wavelengths. The Moon's surface is quite stable, so optical interferometers should be able to operate there (Fig. 6.4). The far side of the Moon is perpetually shielded from low-frequency noise from the Earth, so may become the place of choice for radio telescopes (Fig. 6.5) and long-wavelength infrared observations. At the lunar poles, access to low temperature cold traps could enable very large infrared telescopes to be operated at perpetual cryogenic temperature. Optical and radio telescopes serviced by a polar outpost, but located at reasonable beyond the pole as viewed from Earth could avoid electromagnetic interference from Earth.

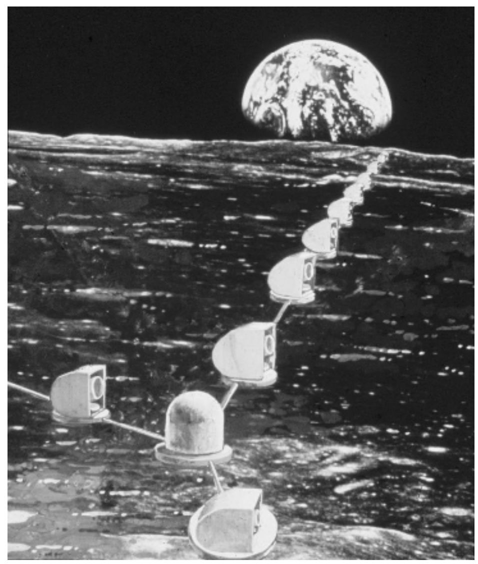

Figure 6.4. Lunar optical interferometer. The individual telescopes send light to the central beam combination dome, where the interferogram would be constructed. Individual telescopes could be separated by 100 to 1000 m.

Although the Moon appears to offer significant advantages for astronomy, astronomers have not focused much attention on the possibility of lunar observatories, preferring to develop concepts that can be deployed in deep space. These concepts include very light-weight "gossamer" structures and space-based interferometers. The Next Generation Space Telescope (Webb Space Telescope), which is planned for the decade of 2000 to 2010, would place an observing system in the Sun-Earth L-2 Lagrange point (Goddard Space Flight Center 1999). In a subsequent generation of telescopes, instruments such as NASA's "Terrestrial Planet Finder" (Jet Propulsion Laboratory, 2000) are being considered that would have the capability of resolving earth-sized planets around nearby stars. Such instruments require light-collecting areas of 1000 m^2 or greater. The technological problems of establishing, maintaining, and operating such telescopes will be enormous. Both space and lunar telescope facilities are subject to degradation from micrometeoroids; however, degradation will be slow and the telescopes are likely to be made of segments, which could be replaced. Further examination of the tradeoffs between deep space facilities and facilities on the Moon are required.

Figure 6.5. Lunar radio telescope fills a lunar crater on the far side.

The principal arguments against siting a telescope on the Moon (van Susante 2002) appear to be that it would cost more (due to additional transportation to the lunar surface), that a significant dust problem exists on the Moon, that thermal problems due to changing solar illumination will degrade the telescope, and that an observatory farther out in the Solar System is required to avoid contamination by light scattered from interplanetary dust. In a strategy of lunar development that includes lunar propellant production, the additional cost argument is diminished. If it becomes feasible for a tourist to go to the Moon, astronomical facilities are likely to be affordable. The dust problem can be solved by appropriate protective measures during nearby operations. Thermal problems can be mitigated by locating observatories in polar regions, perhaps in permanently shadowed craters. Deep space locations of telescopes such as the Sun-Earth L1 point will be more difficult operationally if human maintenance is required, owing to the greater distance and longer transfer times from Earth and because few other activities would be planned there. On the Moon, particularly once other lunar activities are underway, access should be quick and relatively inexpensive. The opportunity to draw on infrastructure provided for a lunar outpost may reduce the cost of operating the instruments. Technicians supported largely by other programs might be available to maintain and repair instruments. Vehicles provided for geological exploration could also carry maintenance crews to visit ailing astronomical instruments. Power might be provided from central power facilities.

We do not yet know enough about the Moon and the problems of emplacement and operation of a lunar telescope to settle these issues, however, future exploration can be directed at resolving uncertainties and reducing costs. These include (a) characterizing lunar cold traps to validate their usefulness for astronomy; (b) determining the leakage of radiofrequency energy around the limbs of the Moon, to help determine the location of a low frequency radio observatory; (c) developing lunar resources for practical applications in construction of telescopes and reducing transportation costs; and (d) developing adequate power and communications infrastructures that allow operation of lunar observatories. If telescope mirrors can be fabricated on the Moon from lunar materials, more rapid expansion of lunar telescope capabilities would be feasible.

A variety of intriguing experiments in space physics, high-energy physics and cosmology are discussed by Potter and Wilson (1990). These opportunities take advantage of the lunar environment and the availability of lunar materials. Potential opportunities include studying the Earth's magnetosphere, constructing cosmic ray and neutrino telescopes, and measuring the half-life of the proton. Many of the proposed experiments could only be carried out on the Moon using natural lunar materials as important parts of the system. A proton-decay detector, for example, could require many tons of detector material (rock, water) buried 100 m below the surface, where the natural background radiation would be very low.

The use of the Moon as a platform for observatories is dependent on the preservation of the appropriate environment for the telescopes, in particular, the maintenance of pristine, high-vacuum conditions, which might be altered by large-scale resource extraction activities. This is discussed further below.

3. TRANSPORTATION BY ROCKET IN THE EARTH-MOON SYSTEM

Situated at an average distance of only 384,000 km from Earth, the Moon's location allows it to be reached in a 3–4-day trip from Earth using current technologies. The Moon provides a natural location for a human outpost or experimental station as humans test their capabilities for long-duration missions beyond low-Earth orbit. At such a station, both humans and machines can be tested in a realistic space environment. The Apollo program landed six crews of two persons each on the Moon for very short periods of time. The total amount of time spent on the lunar surface by all crewmembers was approximately 162 person hours. By contrast, trips to Mars using current rocket systems (including nuclear rockets) require either very long transit times or long stays (up to ~500 days) on the surface. Long-duration missions in an Earth-orbiting space station and long stays on the surface of the Moon are the most relevant simulations of human trips to Mars and further outward into the Solar System (Stafford 1991).

The Earth–Moon Lagrange points may provide useful transportation nodes. Trip times from the Earth for humans are reasonable (3 days), any location on the Moon can be reached at any time (about a day after leaving L-1), and a station located at L-1 can provide a safe haven to which lunar explorers can retreat in case of an unresolvable emergency on the Moon. L-1 lies outside the Earth's Van Allen radiation belts, in which the radiation environment is elevated, so it should be possible to establish a long-term outpost. It can provide a starting point for very low energy (but extended time) transfers to the Sun–Earth and other Earth–Moon Lagrange points (Lo and Ross 2001). L-1 makes a good location for transferring from one kind of space transportation system (e.g., electric propulsion) to another (e.g., chemical propulsion).

In traveling through space, the energy required for going from one orbit to another is the dominant factor that determines the size of the propulsion system. The energy required for an orbit change is related to the mass of the spacecraft and exponentially increases with the velocity change (ΔV) that must be imparted to the spacecraft. Breaking into or out of a "gravity well" associated with a planet is the most energy intensive step in reaching another planet or the Moon, as the required velocity changes are the greatest.

In going from the surface of a planet to space, chemical propulsion systems that are relatively inefficient, but can provide the high thrust needed to break away from gravitational forces, are required. Within space, chemical propulsion may be utilized, but low thrust systems, such as solar electric propulsion systems, may also play a part. The low thrust systems can have high efficiency, so they require lower amounts of fuel, but the fuels tend to be exotic (e.g., Xenon). If they are used to leave the gravitational field of a planet, the low thrust systems require very long transfer times. The SMART-1 mission, utilizing solar-electric propulsion, required about 10 months to go from Earth to Moon (Foing 2004). For quick trips in the vicinity of the Earth and Moon, chemical propulsion currently appears to be the best choice.

A variety of vehicles and systems have been studied for reusable space transportation systems. A recent example of such considerations is the OASIS study led by the Langley Space Center in 2001 (Troutman 2002). This concept utilizes a vehicle that can be propelled either by cryogenic propellants (H_2/O_2) or by electric propulsion, giving it additional flexibility for certain missions.

When utilizing chemical propellants, such as could be produced from lunar resources, the amount of propellant required can be calculated from what is known as the rocket equation (Larson and Wertz 1992).[1] This equation can be used to relate the amount of propellant required to the mass of the spacecraft and its payload and to the velocity change, ΔV. A very simplified calculation (which ignores complexities in spacecraft design) can be used to demonstrate the effectiveness of lunar propellant in the Earth-Moon system. The rocket equation takes into consideration the fact that in accelerating a rocket, some of the propellant is needed to accelerate the rest of the propellant as well as the payload. Using this equation and the characteristics of spacecraft, if the Apollo missions could have refueled on the Moon for their return to Earth, about half of the launch mass would have been required, that is, the Saturn-V launch vehicle could have been half as large. If, in addition, lunar propellant is transferred to a fuel depot in space, such as at L-1, the requirement for launching payloads from Earth is halved once more. The availability of propellant in space would also be conducive to reusable in-space transfer vehicles. If lunar propellant were used in reusable transfer vehicles going from low Earth orbit to L1 to Moon and return, the mass of the system launched from Earth can be less than one tenth of the scale of Apollo to carry the same lunar module from the Earth to Moon and return (Duke et al. 2004).

Once a productive facility is installed on the Moon, it may become economically feasible to transport other lunar products into space. Exporting material products, such as propellants, from the Moon is a more difficult economic problem than simply using products on the Moon, because about as much propellant must be produced as the payload being launched. However, if a vehicle that is reusable and fueled on the Moon from lunar resources can be developed, transporting propellant to lunar orbit, a Lagrange point, or GEO is economically favored over bringing propellant from Earth. Blair et al. (2002) examined such a case. Their scenario demonstrated a performance advantage for lunar propellant over Earth propellant, with economic returns at sufficiently large propellant demand.

The low gravity field and lack of atmosphere on the Moon could allow electromagnetic launchers (Billingham and Gilbreath 1979; O'Neill 1989) to operate at very low energy cost. Electromagnetic propulsion systems have been demonstrated in the laboratory to be able to achieve accelerations of 500-g to 1800-g (Space Studies Institute 1990). If the electromagnetic launcher can produce an acceleration of 500-g (g = 9.8 m/sec^2), lunar escape velocity can be reached with an accelerator 587 m in length, at 1800-g the accelerator would be 160 m in length. Once launched to space, the objects launched from the Moon must be collected. In general, the dispersions associated with minor deviations at launch lead to rather large dispersions in space, which would require propellant if all the objects were to be collected. Heppenheimer (1985) showed that certain locations on the Moon could yield orbits that converged upon a single point in space and that high accuracy could be attained for payloads launched to L-2, optimizing the capability to assemble many payloads at that point without expending large amounts of energy.

Two major strategies for transportation from the Moon can be discerned from the above comments. In the first, a reusable H_2/O_2 vehicle that could be fueled on the Moon could be utilized for round trips carrying payloads to a Lagrange-point station. If propellant were also available at the Lagrange-point station, the amount of propellant that must be transported from

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[1] The amount of propellant required can be computed from the "rocket equation," which can be expressed as $M_i/M_f = \exp(\Delta V/g{\cdot}I_{sp})$, where M_i is the initial mass (rocket plus payload plus propellant) and M_f is the final mass (rocket and payload), ΔV is the change in velocity, g = 9.8 m/sec^2 is the acceleration of gravity at the Earth's surface and I_{sp} is specific impulse (determined at the Earth's surface). The I_{sp} of the Space Shuttle's main engines, which burn liquid oxygen and liquid hydrogen, is 460 s; a typical chemical rocket burning hydrocarbons and oxygen, 360 s; and a solid rocket, 310 s. Low thrust propulsion systems can have very high I_{sp} (1000-3000), but are not powerful enough to overcome planetary gravity fields and can be used only in free space.

Earth, and therefore the size of the launch vehicle, are substantially reduced. In the mass-driver strategy, a relatively small investment in material and access to large quantities of lunar power could enable this new transportation system. It is clear that the former approach is more feasible in the near term and, in the far term, a transportation system that does not use non-renewable lunar resources would be more desirable.

4. THE DEVELOPMENT AND USE OF LUNAR RESOURCES

The availability of lunar material resources and power is a crosscutting idea that has implications for each of the development themes listed above in Section 2. Here we examine lunar resource availability, the technology needed to access these resources, and the manufacturing capabilities that would be developed on the Moon or in space to process lunar materials.

4.1. What are the lunar resources?

The rocks of the Moon contain all of the elements found on the Earth; however, many very useful elements, such as copper, gold, chlorine, and boron, which have been concentrated by natural processes on the Earth, are in dispersed form on the Moon. Humans ultimately will use only small proportions of the available resources of the Earth and Moon, but the natural concentration mechanisms are very important economically, and civilization on Earth would have been significantly retarded if these elements did not occur in natural concentrations. Nevertheless, many useful elements exist in the rocks of the Moon in substantial concentrations. Others may be obtained as byproducts of the processing of lunar regolith and rocks for other purposes.

The regolith in both highlands and mare regions could be the primary source for many materials, particularly iron, titanium, silicon, and sodium from mare regolith and silicon,

Table 6.4. Common lunar rock chemical compositions.

	Mare Rocks				***Highland Rocks***					
	High-Ti	**Low-Ti**	**Very-Low-Ti**	**Al-rich**	**Anortho-site**	**Norite**	**Tracto-lite**	**KREEP basalt**	**QMD**	**Gran-ite**
SiO_2	39.7	45.8	46.0	46.4	45.3	51.1	42.9	50.8	56.9	74.2
TiO_2	11.2	2.8	1.1	2.6	<0.02	0.34	0.05	2.2	1.1	0.33
Al_2O_3	9.5	9.6	12.1	13.6	34.2	15.0	20.7	14.8	6.4	12.5
Cr_2O_3	0.37	0.56	0.27	0.4	0.004	0.38	0.11	0.31	0.16	0.002
FeO	19.0	20.2	22.1	16.8	0.50	10.7	5.0	10.6	18.6	2.32
MnO	0.25	0.27	0.28	0.26	0.008	0.17	0.07	0.16	0.28	0.02
MgO	7.8	9.7	6.0	8.5	0.21	12.9	19.1	8.2	4.7	0.07
CaO	11.2	10.2	11.6	11.2	19.8	8.8	11.4	9.7	8.3	1.3
Na_2O	.38	0.34	0.26	0.4	0.45	0.38	0.20	0.73	0.52	0.52
K_2O	0.05	0.06	0.02	0.01	0.11	0.18	0.03	0.67	2.17	8.6
P_2O_5	0.06	0.05	—	—	—	—	0.03	0.70	1.33	—
S	0.19	0.09	—	—	—	—	—	—	—	—
Total	99.7	99.7	99.7	100.2	100.6	99.9	99.6	98.9	100.5	99.9
Ref.	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)

References: (1) Average of Apollo 11 and 17 low-K high-Ti mare basalts (Haskin and Warren 1991); (2) Average of Apollo 12 and 15 low-Ti basalts (Haskin and Warren 1991); (3) Luna 24 rock fragment 24174,7 (Taylor et al. 1991); (4) Apollo 14 aluminous mare basalt 14053, with Cr and Na from average of 14321 group 5 (Taylor et al. 1991); (5) Typical anorthosite, 60025 (Table A5.32, Papike et al. 1998); (6) Typical norite, 77075 (Table A5.33, Papike et al. 1998); (7) Troctolite, 76535 (Table A5.33, Papike et al. 1998); (8) KREEP basalt 15386 (Table A5.35, Papike et al. 1998); (9) Quartz monzodiorite (Table A5.35, Papike et al. 1998); (10) Granitic rock fragment (Table A5.36, Papike et al. 1998) calcium, and aluminum from highlands regolith. Production of metallic elements from any of these yields byproduct oxygen. KREEP basalts and rare differentiated rocks associated with them are potential sources of several minor elements, such as phosphorous, rare earth elements, and zirconium (e.g., Meyer 1977).

Essentially all of the samples so far collected on the Moon are fragments (some of them quite large) of rocks found in the regolith, associated with glasses/agglutinates produced by micrometeoroid bombardment on the lunar surface. The range of rock types found in lunar regolith, therefore, indicates the range of primary rocks that could provide useful materials and could be the targets for detailed exploration. The mare rocks sampled to date are all basalts. The highland rocks cover a great range, from anorthosites (principally consisting of feldspar) to norite and troctolite that have different major minerals (pyroxene and olivine, in addition to feldspar). The KREEP, QMD (quartz monzodiorite or *monzogabbro*) and granite are chemically evolved rocks that are related to magmatic differentiation within the Moon. The chemical compositions of the principal rock types are characterized in Table 6.4 and discussed in detail in Chapters 2 and 3.

Most lunar resources are not highly concentrated. Therefore, it is important to understand the chemical nature of their minerals, which constitute separable and concentratable portions. Table 6.5 gives the compositions of some typical minerals in lunar rocks. It is likely from these minerals that some of the less abundant elements could be extracted. Among these would be Ti from ilmenite; Mg from olivine; Na, K, Sr and Ba from plagioclase and potassium feldspar; and

Table 6.5. Major-element compositions of lunar minerals (from Papike et al. 1991).

	Pyrox	***Pyrox***	***Pyrox***	***Pyrox***	***Oliv***	***Oliv***	***Plag***	***Plag***	***K-spar***	***Ilm***	***Sp***	***Apat***	***Whit***
SiO_2	49.3	47.1	53.0	54.3	35.4	39.9	44.5	44.6	60.9	0.23		0.72	0.41
TiO_2	3.2	0.86	0.51	1.1	0.00	0.00				53.0	6.3		
Al_2O_3	2.5	0.72	0.24	0.66	0.00	0.00	35.2	35.2	22.5		11.0		
Cr_2O_3	0.45	0.06	0.09	0.64	0.11	<0.02				0.52	43.8		
FeO	11.0	41.0	22.6	4.8	33.8	12.0	0.81	0.20	0.13	45.1	33.3	0.92	1.0
MnO	0.08	0.67	0.62	0.15	0.36	0.1				0.45	0.27		
MgO	14.8	2.3	21.9	16.8	30.1	47.1	0.08	0.06	0.0	0.75	3.9	0.35	2.9
CaO	17.95	8.0	0.80	22.3	0.36	<0.02	19.2	20.0	3.9	0.10		54.4	39.3
Na_2O	0.0	0.0	0.0				0.58	0.35	3.5				0.14
K_2O							0.02	0.01	8.0				0.02
P_2O_5												39.1	42.14
BaO									1.2				
V_2O_3											0.74		
Y_2O_3												1.5	3.7
La_2O_3													1.5
Ce_2O_3													3.8
Nd_2O_3													2.3
Cl												1.8	0.04
F												1.1	0.14
Total	99.3	100.7	99.8	100.8	100.1	99.1	100.4	100.4	100.1	100.0	99.3	99.9	97.7
Ref.	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)

References: (1) Augite in Apollo 11 high-Ti basalt 10058; (2) Sub-calcic augite in Apollo high-Ti basalt 10058; (3) Orthopyroxene in ferroan anorthosite 15415; (4) Orthopyroxene in norite 78235; (5) Olivine in low-Ti mare basalt 12035; (6) Olivine in highlands troctolite 76535; (7) Plagioclase feldspar in low-Ti mare basalt 12021; (8) Plagioclase feldspar in ferroan anorthosite 60015; (9) K-feldspar in granite 12013; (10) Ilmenite in high-Ti mare basalt 10058; (11) Spinel in low-Ti basalt 12063; (12) Apatite in breccia 14321; (13) Whitlockite (RE-merrillite) in KREEP-rich sample 12013

Mn and Cr from pyroxenes. Chromium might also be recovered from spinel, which is ubiquitous in mare basalts and is found also in anorthosites and troctolites. Chrome spinel and ilmenite concentrations, formed by crystal settling during differentiation of basalt flows or intrusions, could occur (Taylor 1990) but have not been reported. Phosphate minerals may be a useful source of rare earth elements (whitlockite) or halogens (apatite). Whitlockite (RE-merrillite) contains up to 4 wt% Ce_2O_3, the most abundant rare earth element. Apatite contains 3–4 wt% F and Cl. These have been observed as minor or trace minerals in rocks studied to date, but future exploration could search for higher concentrations and beneficiation techniques used to concentrate them. If mineral beneficiation is to be used, rocks rather than regolith may be the best source, as distinct mineral fragments in regolith are less abundant than in the source rocks.

Solar-wind atoms implanted in the grains of the lunar regolith, and grain-surface deposits produced by volcanic or impact vaporization, may constitute unique lunar resources. Regolith compositions generally mimic the bulk composition of the underlying rocks; however, the volatile elements He (and other noble gases), C, H, and N are ubiquitous in the regolith, having been implanted in the surfaces of regolith grains by the solar wind. These elements have low abundances (Table 6.6), but the solar-wind species are strongly surface-correlated (as shown in Table 6.7 by carbon variations with grain size). Most regolith grains have 1000 angstrom thick radiation-damaged rims that contain the solar-wind implanted atoms (Bibring et al 1974; Keller and McKay 1997). Consequently, the finest-grained fractions (<20 μm) of the regolith have significantly higher concentrations of He, H, C, N, and S. Solar-wind volatiles, most notably H and He, are retained preferentially by ilmenite (Cameron 1993). Other elements, volatilized and redeposited as surface coatings on regolith particles by micrometeorite impact, also may be concentrated on grain surfaces. Examples include rare volatile elements such as Cd, Hg, and Zn (Table 6.7). Grain surfaces are also enriched in vapor-deposited Fe^0 (e.g., Pieters et al. 2000;

Table 6.6. Typical concentrations (in ppm) of solar wind volatile species in lunar regolith samples (Haskin and Warren 1991).

	H	*He*	*C*	*N*	*Ne*	*Ar*
Apollo 11	20-100	20-84	96-216	45-110	2-11	1.3-12
Apollo 12	2-106	14-68	23-170	46-140	1.2-6	0.5-4.6
Apollo 14	67-105	5-16	42-225	25-130	0.14-1.6	0.4-2.2
Apollo 15	13-125	5-19	21-186	33-135	0.6-108	0.5-2.7
Apollo 16	4-146	3-36	31-280	4-209	0.4-1.2	0.6-3
Apollo 17	0.1-106	13-41	4-200	7-94	1.2-2.7	0.6-2.6

Table 6.7. Concentrations of surface elements as a function of size fraction of regolith grains in sample 72501.

	C (ppm)	*Cd (ppb)*	*Hg (ppb)*	*Zn (ppm)*
Bulk soil	71	39	3.1	17
<37 μm	236			
7-15 μm		72	6.3	33
< 2 μm		106	22	54
Ref.	(1)	(2)	(2)	(2)

References: (1) DesMarais et al. (1975); (2) Krahenbuhl (1977)

Taylor et al. 2001a). Keller and Clemett (2001) and Taylor et al. (2001a,b) recently showed that the composition of the <20 μm fraction is significantly affected by these redeposited elements.

Volcanic glasses, such as the pyroclastic[2] orange glass discovered at the Apollo 17 site, are mare basaltic in bulk composition (Table 6.8), though they tend to have even lower Al than do mare basalts (see Chapter 3). Most importantly, they also contain surface-correlated phases consisting of volatile elements such as S, Ag, Cd, Zn, and Br (e.g., Baedeker et al. 1974; Wasson et al. 1976; Delano 1986). These phases were deposited from the volatile vapor phase associated with the eruption of the particles, and are enriched in elements that are relatively rare on the Moon (Table 6.9). In most cases, bulk deposits of the orange (Apollo 17) and green (Apollo 15) glasses are enriched in volatile elements. The surfaces of the glasses are enriched compared to their interiors by factors of 3 to over 400 (Table 6.9). This suggests that chemically etching or physically abrading volcanic deposits may be an effective way to extract rare volatile elements needed for industrial processes. For a few elements, notably S, bulk concentrations are lower than in mare basalt samples, although their concentrations are still greater in the surfaces than interiors of individual glass spheres.

The lunar surface has been bombarded by meteoritic material and typical regolith contains significant concentrations (2%) of chondritic meteoritic material (Heiken et al. 1991). Metallic iron from meteorite sources may become a source on the Moon for Fe, Ni, and noble metals; however, Fe^0 in the regolith is derived from several sources, including comminution of basalts, which contain small amounts of native Fe, from nanophase Fe (e.g., Morris 1977) formed in the production of agglutinates, and as vapor-deposited nanophase Fe on the surfaces of most soil particles in a mature soil (Taylor et al. 2001a,b).

Results from the Lunar Prospector mission have shown that elevated hydrogen concentrations are likely to exist at the lunar poles, perhaps in association with shadowed craters (Feldman et al. 2000, 2001). Areas with the lowest epithermal neutrons are interpreted as areas with elevated hydrogen contents. Because water molecules released anywhere on the lunar surface have a high probability of migrating to polar cold traps (Watson et al. 1961; Arnold 1979; Butler 1997), a strong possibility is that the hydrogen is associated with water-ice deposits. The Lunar Prospector data suggest that water concentrations may be in the range of 1 to 2%, with local concentrations perhaps as high as 10% (Feldman et al. 2001). Information is not yet available with sufficient precision to designate areas where exploration for water would be most productive. Additional remote sensing should help to delineate water concentrations. Radar mapping from a polar orbiter could map the subsurface at a resolution useful for characterizing the distribution of ice (Nozette et al. 2001), if the concentrations of ice are 30% or more.

Arnold (1979) showed that there was enough water brought to the surface by micrometeoroids and comets or produced on the Moon by interactions of solar-wind hydrogen with lunar minerals to have deposited several meters of water in the cold traps over the past 2 to 3 billion years. However, there are also removal mechanisms such as sputtering (Lanzerotti et al. 1981) and activation by Lyman α radiation (Morgan and Shemansky 1991), and the calculated removal rates are close enough to the calculated deposition to leave the question in doubt. The form of the hydrogen produced by solar-wind interactions has not been determined. Crider and Vondrak (2000) have suggested that much of it may be in the form of OH^- ions, which would not be readily removable by sputtering or Lyman α radiation, and even thin layers of impact debris could shield ice from Lyman α radiation. If water has been deposited in the cold traps, other volatile elements may be concentrated there as well. Comets contain

[2] Pyroclastic refers to the process of hot-ash extrusion from volcanoes. The lunar pyroclastic glass is believed to have formed in a process similar to fire-fountaining observed in terrestrial volcanoes, where gases disperse and eject droplets of melt that quickly freeze to form glass.

Table 6.8. Compositions of some lunar volcanic glass groups (Delano 1986), listed in order of increasing TiO_2.

	(1)	*(2)*	*(3)*	*(4)*	*(5)*	*(6)*	*(7)*	*(8)*	*(9)*	*(10)*
SiO_2	48.0	44.0	42.9	40.8	40.5	39.4	38.8	37.3	35.6	33.4
TiO_2	0.26	0.91	3.5	4.6	6.9	8.6	9.3	10.0	13.8	16.4
Al_2O_3	7.7	6.9	8.3	6.2	8.0	6.2	7.6	5.7	7.2	4.6
Cr_2O_3	0.57	na	0.59	0.41	0.63	0.67	0.66	0.63	0.77	0.84
FeO	16.5	20.2	22.1	24.7	22.3	22.2	22.9	23.7	21.9	23.9
MnO	0.19	0.23	0.27	0.30	0.25	0.28	0.29	na	0.25	0.30
MgO	18.2	19.5	13.5	14.8	12.6	14.7	11.6	14.3	12.1	13.0
CaO	8.6	7.4	8.5	7.7	8.6	7.5	8.6	7.6	7.9	6.3
Na_2O	nd	0.1	0.45	0.42	0.39	0.41	0.39	0.31	0.49	0.05
K_2O	nd	nd	nd	0.10	nd	0.04	nd	nd	0.12	0.12

nd = not detected; na = not analyzed

Sample: (1) Apollo 15 green C; (2) Apollo 17 green; (3) Apollo 15 yellow; (4) Apollo 14 yellow; (5) Apollo 17 yellow; (6) Apollo 17 orange; (7) Apollo 17 orange; (8) Apollo 11 orange; (9) Apollo 15 red; (10) Apollo 12 red.

Table 6.9. Concentrations of surficial volatile elements on volcanic glasses.

	Zn ***(μg/g)***	***Ga*** ***(μg/g)***	***Ge*** ***(ng/g)***	***Cd*** ***(ng/g)***	***In*** ***(ng/g)***	***Ir*** ***(pg/g)***	***Au*** ***(pg/g)***	***F***[3] ***(μg/g)***
Apollo 17 orange glass[1]								
Interior	19	2.8	161	32	0.80	210	274	50
Surface	434	33.1	880	1150	62.4	650	860	700
Apollo 15 green glass[2]								
Interior	1.6	2.9	12.3	1.6	0.2	260	50	40
Surface	113	10.9	668	678	6.9	1200	5420	600
Other elements concentrated on surfaces of glass beads, excluding solar-wind components[4]:		B Na S Cl	K Cu Se Br	Ag Sb Te I	Hg Pb B Ta			

Note: Surface concentrations analyzed by leaching and etching; interior concentrations measured on residues. In both cases, about 10% of the glass spheres was etched away.

References: [1]Wasson et al. (1976); [2]Chou et al. (1975); [3]Goldberg et al. (1976); [4]Delano (1986)

abundant volatiles (C, N compounds), some of which might be condensed in the cold traps. Volatile metallic elements, such as Hg, may also be concentrated (Reed 1999).

Sources and sinks for potential resources cannot be resolved by modeling, but must be established by surface exploration. To prepare the way for resource utilization, it will be necessary to establish the lateral and vertical distribution of hydrogen and water in areas that are amenable to resource recovery, to determine the form of hydrogen and its compounds, and to determine the presence of other potentially valuable materials in the polar cold traps. There are also scientific investigations of significance that could be carried out in conjunction with these measurements, particularly investigation of the vertical distribution (stratigraphy) within the hydrogen deposits and the isotopic characteristics of the hydrogen-containing products as indication of their source and depositional history.

Table 6.10 provides a list of resources, their potential host material, estimated grades, and theoretically possible upper limit on grade. A discussion of how these estimates were made is given by Taylor and Martel (2003). Interesting, detailed discussions of lunar resources can be found in Haskin et al. (1993) and Fegley and Swindle (1993).

4.2. Distribution of lunar resources

The distribution of useful resources on the Moon is a result of magmatic and impact processes. Our understanding of the potential distribution of lunar resources is based on results of remote-sensing analyses, calibrated with studies of lunar samples. For a number of elements, including Fe, Ti, and Th, the global distribution is known by observation from Apollo (e.g., Metzger et al. 1973), Clementine (e.g., Lucey et al. 1998a, 2000; Giguere et al. 2000), and Lunar Prospector (e.g., Elphic et al. 1998; Lawrence et al. 1998; Prettyman et al. 2001). As the Lunar Prospector data are further reduced, it may be possible to obtain the distribution of

Table 6.10. Potential resources, possible host materials, and their grades.

Resource	*Potential Host Material*	*Grade (average)*	*Grade (max. meas.)*	*Grade (possible)*[1]
Solar wind volatiles				
H	regolith	50 μg/g	150 μg/g	150 μg/g
^{3}He	regolith	4 ng/g	30 ng/g	30 ng/g
^{4}He	regolith	14 μg/	100 μg/g	100 μg/g
C	regolith	124 μg/g	300 μg/g	300 μg/g
N	regolith	81 μg/g	150 μg/g	150 μg/g
Precious metals				
Pd	regolith/breccias	12 ng/g	28 ng/g	60 ng/g
Ir	regolith/breccias	9 ng/g	26 ng/g	50 ng/g
Au	regolith/breccias	6 ng/g	17 ng/g	35 ng/g
Iron and ferroalloy metals				
Fe	mare basalts	15 wt%	17 wt%	20 wt%
Ni	regolith	250 μg/g	730 μg/g	1500 μg/g
Co	regolith	35 μg/g	68 μg/g	140 μg/g
W	regolith	370 ng/g	1950 ng/g	3900 ng/g
Mn	mare basalts	0.2 wt%	0.3 wt%	0.3 wt%
Cr	mare basalts	0.2 wt%	1.1 wt%	2 wt%
Cr	highland norites	0.2 wt%	0.3 wt%	15 wt%
Non-ferrous metals				
Ti	High-Ti mare basalts	7 wt%	8 wt%	16 wt%
Al	anorthosite	18 wt%	—	18 wt%
	average highlands	15 wt%	—	15 wt%
Zn	volcanic glass	10 μg/g	400 μg/g	800 μg/g
Cd	Volcanic glass	16 ng/g	1150 ng/g	2200 ng/g
Non-metals				
Ce (rep. REE)	Evolved ig. rocks (KREEP)	175 μg/g	700 μg/g	3500 μg/g
Ba	Evolved ig. rocks (KREEP)	0.1 wt%	0.45 wt%	2 wt%
K	Evolved ig. rocks (KREEP)	0.8 wt%	1.8 wt%	9 wt%
P	Evolved ig. rocks (KREEP)	0.6 wt%	2.2 wt%	10 wt%
Th	Evolved ig. rocks (KREEP)	22 μg/g	50 μg/g	500 μg/g
Zr	Evolved ig. rocks (KREEP)	0.1 wt%	0.7 wt%	3.5 wt%

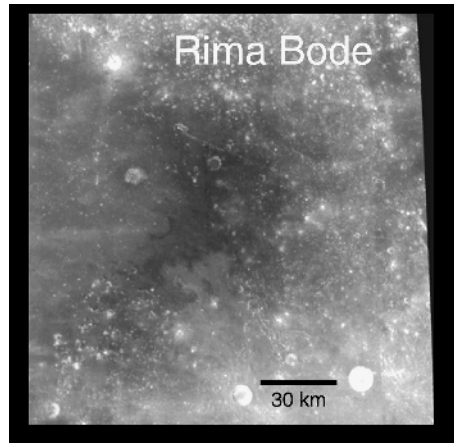
Notes: Data from Haskin and Warren (1991); Fegley and Swindle (1993); Papike et al. (1998). [1]"Possible Grade" estimated by extrapolation from existing data and knowledge of the processes that concentrate the elements. No data confirm these estimates.

additional elements such as Mg. For other elements, estimates can only be made by deducing the rock type indicated by the remote-sensing data and estimating elemental abundances based on their known distribution in lunar samples. The spatial resolution for most elements in the Lunar Prospector gamma ray spectrometer results is quite coarse (>25 km, see Chapter 2), as will be the X-ray spectrometry data expected from SMART-1. Thus, available data can indicate general areas where resources may be located, but not specific areas of maximum concentration. For elements present in concentrations of 1% or more, an area 100 m^2 mined to a depth of 1 m, could yield several hundred tons or more of product, which is larger than anticipated early uses. Thus, the 100 m resolution of the best available data from Clementine is potentially useful in locating mining operations, but locating small areas of higher ore grade will require higher resolution data sets. Such detailed studies may be best carried out with surface investigations.

The processes of formation of the lunar regolith have caused lateral mixing that reduces the sharpness of unit boundaries (e.g., Li and Mustard 2000) and the agglutinate-containing and vapor-deposited nanophase Fe limits spectral resolution. Sub-regolith rock type identifications by remote sensing are best done by analyses of materials excavated by fresh impact craters (e.g., Tompkins and Pieters 1999; Staid and Pieters 2000; Pieters et al. 2001). For small craters, the maximum depth of excavation of rocks exposed in the rims of impact craters is about half of the diameter of the crater. This material can mostly be observed within about one crater diameter of the crater rim. The resolution available in the Clementine UVVIS images (about 100 m), therefore, limits the depth resolution of crater composition mapping to >50 m from the surface. For larger craters, the depth/diameter ratio is smaller. The highest-resolution data from Lunar Prospector (e.g., thorium) may ultimately be mappable to a resolution of 15 km (A. Binder, pers. comm..), and so may be suitable for distinguishing layers that are deeper than about 10 km. Pieters et al. (2001) used Clementine UVVIS data to distinguish between anorthosite, gabbro, and olivine-bearing rocks in the South Pole-Aitken Basin. Lunar Prospector data clearly depict materials that likely to have formed at depth within the lunar crust were excavated by the Imbrium and South Pole–Aitken Basins (Pieters et al. 2001). More work of this type may be useful in locating deep layers that could contain potential resources.

Lunar pyroclastic deposits are typically observable from orbit as very dark deposits distributed across broad highland regions or as dark-halo craters within ancient floor-fractured craters (Fig. 6.6; e.g., Head 1974). Most of these deposits are Fe- and Ti-rich, but unrecognized pyroclastic deposits of other compositions may exist (e.g., Gaddis et al. 1985). The association of many pyroclastic deposits with Imbrian-aged floor-fractured craters (e.g., Head and Wilson 1979) or ancient lunar volcanic deposits (e.g., Whitford-Stark 1990; Hiesinger et al. 2000) suggest that most of these deposits are of late Imbrian age, generally 3.2 to 3.7 Ga. These ancient pyroclastic deposits have mature regolith surfaces, and they exhibit the subdued mafic absorption bands comparable to those of mature maria and highlands in the Clementine UVVIS data. The majority of these deposits consist of fragmented basalts, with substantial components of iron-bearing mafic minerals (clinopyroxene, olivine) and smaller amounts (if any) of iron-bearing volcanic glass (Gaddis et al. 2000, 2003). In addition to these mare-like deposits, two additional classes of pyroclastic deposits stand out spectrally, but are rare. These are the "black-bead" deposits similar to the devitrified orange glass found at the Apollo 17 site and the spectrally red glass-rich deposits that occur at Aristarchus Plateau. Although these deposits are areally extensive, this apparently distinctive composition is limited to a few deposits in the central nearside of the Moon. These results suggest that the pyroclastic deposits most commonly recognized as having commercial potential, such as the black-bead deposits at Taurus Littrow that have been suggested as sources of O, Fe, and Ti (e.g., Hawke et al. 1990; Allen et al. 1996), may be restricted to a few source regions on the Moon.

Remote characterization of the distribution of a valuable lunar material resources is exemplified by recent efforts to map the distribution of ^3He on the Moon (e.g., Johnson et al. 1999).



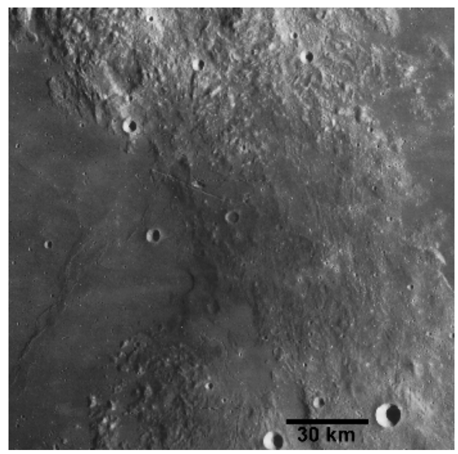


Figure 6.6. Clementine 750-nm images of dark pyroclastic deposits at Rima Bode (top) and in the floor of Oppenheimer crater (bottom) (after Gaddis et al. 2003).

It is well known that He is correlated with Ti content of the lunar regolith due to the preferential retention of solar-wind-implanted ^3He in the ilmenite crystal structure (e.g., Cameron 1987) (Fig. 6.7). The abundance of solar-wind implanted ^3He in the lunar regolith depends on surface or regolith maturity, the amount of solar-wind fluence, and Ti content. Regolith maturity can be assessed through remote-sensing data (e.g., Lucey et al. 1998b). A model of solar-wind fluence combined with maps of surface maturity and TiO_2 content derived from Clementine UVVIS data (Lucey et al. 1998a,b; 2000) can be used to map the approximate concentration of ^3He in the regolith (Fig. 6.8). The highest ^3He abundances are predicted to occur in the farside maria due to greater solar-wind fluence received (Swindle et al. 1992) and in higher TiO_2 nearside mare regions. Areas that show high-TiO_2 content and high maturity are prime locations for extraction of solar-wind volatiles, including H, C, and N.

Another example of lunar resource assessment is provided by efforts to map thorium concentrations established by Apollo and Lunar Prospector gamma ray spectrometers (Plate 2.3). It is currently believed that thorium is principally associated with the KREEP rocks of the Imbrium Basin (e.g., Haskin et al. 2000). It can be inferred from current understanding of lunar rock types that elements that are enriched in KREEP will be concentrated in areas with high Th concentrations (e.g., Jolliff et al. 2000). Among the more interesting of these are Th, U, Zr, and P, which could have significant industrial and agricultural uses. However, the resolution of the Lunar Prospector data is not sufficient to delineate the highest concentrations at scales commensurate with mining operations; surface mapping will be required.

In general, the orbital geochemical mapping tools have resolution too coarse to be used for operational resource mapping, but trends established by these tools correlated to geological features feed back through high-resolution multispectral imaging to useful resource assessment. It is possible to improve spatial resolution for X-ray and γ-ray spectrometers by using collimated instruments and by lowering the spacecraft altitude (W. Boynton, pers. comm.). The Lunar Prospector team has demonstrated that higher resolution can be obtained with more data; however, these improvements are limited by counting statistics, i.e., to improve the data by a factor of two requires four times the data. Active orbital sensing techniques, using energetic beams for probing the surface, may be feasible (Meinel et al 1990), but would require large amounts of energy if conducted from 100 km orbits.

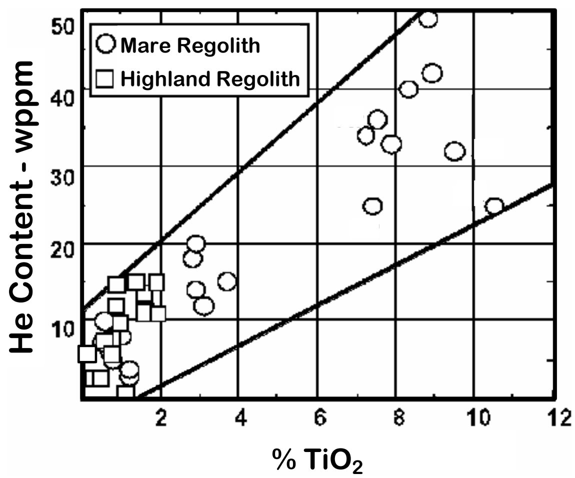


Figure 6.7. Helium content (ppm, weight) in lunar soils as a function of TiO_2 content (after Cameron 1987).

4.3. Prospecting for and processing lunar resources

4.3.1. Surface prospecting for lunar mineral resources. It appears that surface prospecting will be required to detect and characterize sub-surface concentrations of useful minerals. This may not be an issue for major elements, because a few percent variation in grade is not likely to cause changes in the extraction process. However, if minor minerals or subtle features are sought, it will be necessary to collect and analyze many samples to localize sub-regolith sources in mare regions. A procedure might consist of first removing agglutinates magnetically, then separating and analyzing the mineral constituents in a given size fraction of the regolith. The distribution of rock types in many samples of regolith from a local area might allow subsurface deposits of interest to be located.

An alternative approach is to use rovers equipped with analytical devices capable of measuring the abundances of target elements or elements that are diagnostic for the target elements (e.g., Th for the rare earth elements). The rovers would be sent to regions thought on the basis of remote sensing data to be rich in a specific resource. An example of how we might explore the Moon for a specific resource is the search for economic deposits of non-metals (e.g., Th, REE, Zr, P, K). This search could begin by finding the regions richest in Th by using orbital geochemical data. The spatial resolution of orbital γ-ray measurements is about 60 km. A rover could be landed inside a 60-km spatial resolution element that contained a high concentration of Th. The Th might be distributed uniformly, or it might be concentrated locally. The rover would autonomously traverse an assigned region, making measurements of a selected element or elements. For this example, a good choice would be Zr, which is relatively abundant (Table 6.8) and is correlated with Th, rare earth elements, and K. Measurements could be made every 10 or 100 meters. The data would be transmitted to orbiting satellites. The numerous analyses at known locations would allow planetary economic geologists to make contour maps of the abundance of Zr (or another element), thereby mapping out potential concentrations of the elements of interest. Regions of exceptional concentrations would be investigated further.

Another alternative is the systematic analysis of rocks excavated by recent impacts, which can be used to characterize near surface units. For example, the maria were emplaced as a sequence of flows. Some layers may have cooled slowly enough to allow differentiation and concentration of useful minerals. These might be located by systematic study of ejecta from craters. Old, buried mare regolith surfaces that might contain different concentrations of solar-wind products than the surface regolith might also be located in this manner.

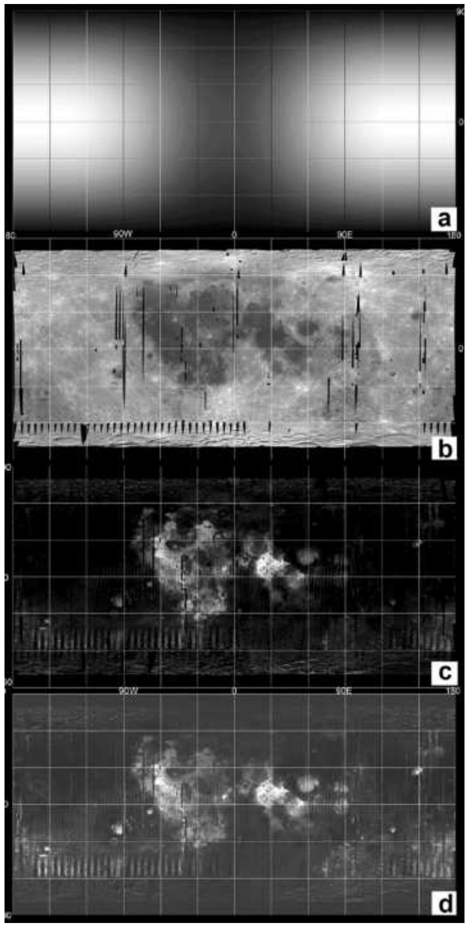


Figure 6.8. Simple cylindrical projections (left side of images corresponds to 180 W longitude; 30-degree grid shown, resolution is 0.25°/pixel) of (a) solar wind fluence model, (b) Clementine 750-nm mosaic; (c) TiO_2 abundance map from Lucey et al. (2000) displayed from 0 to 6 wt%; and (d) ^3He abundance map displayed from 0 to 10 ppb (from Johnson et al. 1999).

On Earth, when concentrations of ore minerals are suspected at depth, drilling is used to delineate the extent of the resource. Studying crater ejecta is an alternative to drilling, using the concept that the impact excavation reveals materials from depth. On the Moon, there will be a tradeoff between exploring for concentrations of trace minerals in subsurface rocks and beneficiation of the already-crushed materials in the regolith. It may be preferable to expend energy on beneficiation, even if it requires that much more regolith be mined and processed, than to go to the next step of processing solid rock, a subject addressed by Chambers et al. (1995). However, if a high concentration of a mineral such as chromite were found in a layered magmatic deposit, other processes, such as those used in hard rock mining on Earth, might be favored.

Surface exploration for hydrogen and water in lunar permanently shadowed craters is a special case, because useful deposits can be within 1-2 meters of the surface. A neutron spectrometer and perhaps ground-penetrating radar, active seismic, or electrical resistivity techniques could be used to characterize the content of hydrogen and possibly water ice. Thermal probes could be employed to sense the presence of condensed volatiles (it is possible that the presence of the sensing system itself, e.g., a rover, would be a sufficient energy source). Drilling and sampling to depths of 1–2 m could be used to determine the extent, thickness and grade of the deposits. All of these tools might be carried aboard a robotic rover, capable of spending many hours within the permanent shadow. The deployment of such a rover may be made feasible by Stirling dynamic isotope power systems (Thieme et al. 2000) that are being developed for outer planet and comet missions.

4.3.2. Mining. Mining is a somewhat misleading term in the context of most lunar-materials processing strategies, because most material will be mined by scooping up regolith, and the scale of activities will be rather small by terrestrial standards. This does not apply to concepts for H or ^{3}He mining, which would require the excavation of very large areas utilizing large machinery, comparable to terrestrial mining of coal and harvesting of grain. Approaches to such large-scale excavation include front-end loaders, scrapers, and continuous excavators (Chamberlain et al 1992).

Modeling of excavation of the lunar regolith (Eagle Engineering 1988; Muff et al. 2001) indicates that excavation is a low-energy process and machines should be able to excavate several times their mass each hour of operation. Most mining would be done during daylight hours at equatorial outposts. At a polar outpost, where mining in permanent shadow is required, all activities must be done in the dark. Issues associated with mining include the ability to provide energy to mobile equipment, so that mining equipment can operate flexibly, as well as maintenance and repair, which is a significant problem for terrestrial mining equipment. Henley et al. (2002) proposed laser-power beaming as a method of transmitting energy to a mobile system operating in permanent shadow. Schrunk et al. (1999) have proposed more complex lunar infrastructures based in part in transmitting power from point to point on the Moon.

4.3.3. Transportation. If the mine is separated from the processing plant by a significant distance, a surface transportation system is required. A mechanized hauler is a convenient and efficient way to provide surface transportation. Such systems, operating in the low-gravity field of the Moon, can haul more of a load per unit mass of equipment than equivalent haulers on Earth (Eagle Engineering 1988). The construction of roadways can make haulers even more effective. In special situations, for example, where the mining site is at higher elevation than the processing site, gravity can be used effectively to transport regolith to a reactor. A tramway, for example can have gondolas that are filled with material and fall in the Moon's gravitational field, simultaneously delivering regolith to the processing facility and pulling empty gondolas to the top.

If the resource to be extracted is in low abundance, such as the case for solar-wind implanted volatiles, it may not be cost-effective to haul material long distances to processing plants and a mobile processor might well be a more effective solution. However, typically, the energy required for extraction in these cases is high, so means must be found to provide power to the excavator, as proposed for the ^{3}He excavator (Sviatoslavski 1992) or the power-beaming concept of Henley et al. (2002).

4.3.4. Beneficiation. Beneficiation is the term used to designate the processing of an ore to concentrate a particularly useful mineral or element. Examples of beneficiation on the Moon could include: (1) size sorting of regolith to concentrate the fine-grained portions that preferentially retain solar-wind volatiles and native Fe; (2) concentration of ilmenite using electrostatic separation techniques (Agosto 1985), or (3) magnetic separation of Fe-bearing minerals from anorthositic regolith to concentrate anorthite or Fe (Taylor and Oder 1990), and ilmenite from regolith or crushed rock (Chambers et al. 1994). The use of beneficiation is dictated by the economics of the mineral recovery process. If the advantages of using a beneficiation process outweigh the costs and complexities of transporting and operating another piece of equipment on the Moon, the beneficiation technique will be used.

4.3.5. Thermal and chemical processing.

<u>Extraction of oxygen.</u> Most investigations of the extraction of resources from lunar materials have focused on the extraction of oxygen (Table 6.11, from Taylor and Carrier 1992a). Table 6.12 gives characteristic feeds, plant mass, and energy requirements (Taylor and Carrier 1992a,b) for several processes. Each of the plants could produce several times its own mass in a year. Those with smaller masses, including the mass of the energy-production system, would be favored for application on the Moon, due to the high costs of transportation. In ranking processes based on consideration of technology readiness, number of major steps, process conditions, and feedstock requirements, Taylor and Carrier (1992a) selected 8 processes (bold in Table 6.11) as the "best" for further consideration.

Typically, when iron oxide in ilmenite, silicate minerals, or molten regolith is reduced, Fe^0 appears as a byproduct of oxygen production. Because the reducing agents are not abundant on the Moon, they must be recycled and conserved (see Section 4.4.7). The amount of reducing agent can be significant. For example, in the reaction $FeO + H_2 = H_2O + Fe^0$; $H_2O = H_2 + \frac{1}{2}O_2$

Table 6.11. Oxygen and volatile extraction methods (Taylor and Carrier 1992).

Solid/Gas Interaction	Silicate/Oxide Melt
Ilmenite reduction with Hydrogen	Molten Silicate Electrolysis
Ilmenite Reduction with C/CO	Fluxed Silicate Electrolysis
Ilmenite Reduction with Methane	Caustic Dissolution and Electrolysis
Glass Reduction with Hydrogen	Carbothermal Reduction
Reduction of FeO with Hydrogen Sulfide	Magma Partial Oxidation
Extraction of silicates with Fluorine	Li or Na Reduction of Ilmenite
Carbochlorination of silicates	
Chlorine Plasma Reduction of regolith	*Aqueous Solutions*
	HF Acid Dissolution
Pyrolysis	H_2SO_4 Acid Dissolution
Vapor Pyrolysis	
Ion Plasma Pyrolysis	*Co Product Recovery*
Plasma Reduction of Ilmenite	Hydrogen-Helium-Water from Soil

Table 6.12. Scale and energy requirements for selected oxygen plants (Taylor and Carrier 1992).

Processes	***Ore (1000 tonne/yr)***		***Plant Mass (tonne)***	***Energy (MW-yr)***
	Raw	***Process Throughput***		
Ilmenite: High-Ti Mare				
Reduction[2]	210,000	21,000[1]	200	3
CO Reduction	210,000	21,000[1]	225	3.5
CH_4 Reduction	210,000	21,000[1]	225	3.5
Mare or Highlands				
Glass reduction by H_2	160,000	80,000[2]	200	4
Molten silicate electrolysis	5000	5000[3]	70	3
Fluxed molten silicate electrolysis	5000	5000[3]	80	3.5
Vapor Pyrolysis	5000	5000[3]	40	2
Ion Plasma pyrolysis	5000	5000[3]	40	2.5

Notes: [1] Assumes feedstock with 50 wt% ilmenite from an ore with 5% available ilmenite. It is assumed that the iron oxide in 90% of the ilmenite is converted . [2] Assumes soil with 25% glass is beneficiated by a factor of two; assumes 15% FeO in glass and 75% conversion to $Fe° + O_2$. [3] No beneficiation required; Assumes 43 wt% O_2 in regolith with 50% recovery.

the amount of hydrogen needed is 25% of the amount of the oxygen produced per pass. In the case of $FeO + CH_4 = 4Fe^0 + CO_2 + 2H_2O$; $H_2O = H_2 + ½O_2$, the amount of methane required is 50% by amount of oxygen produced. Thus, the processing must be highly effective in the recovery of the reagents or a source of reagents must be found on the Moon. Electrolytic methods using molten regolith do not require reagents, so they avoid the problem of reagent loss; however, electrodes are generally consumed during the operation of an electrolytic cell, and their replacement may be a problem of equivalent severity. Terrestrial electrolytic techniques such as the Hall process for aluminum require catalysts, but these are also consumed slowly in the production process. Pyrolysis techniques (heating to very-high temperatures to evolve metals in a vapor phase) requires a great deal of energy, but might be directly implemented on the lunar surface with concentrated energy from a solar mirror, operating in the lunar vacuum. Tradeoffs between materials and energy will have to be considered before the best processes can be selected.

The hydrogen reduction process has been demonstrated with actual lunar samples. Gibson et al. (1994) produced oxygen by reducing lunar basalt at temperatures of 900-1150 °C. Ilmenite was the primary source of oxygen, with lesser yields from olivine and pyroxene. The total oxygen release ranged from 2.9 to 4.6 wt%. Allen et al. (1994b, 1996) demonstrated oxygen release from 16 lunar soils and 3 volcanic glass samples. Hydrogen reduction at 1050 °C yielded 1.6–4.7 wt% oxygen, with yield directly correlated to each sample's total iron content. Ilmenite-rich mare soils and iron-rich glass samples yielded the most oxygen. However, it should be emphasized that these were experiments conducted in a "batch mode," and were only preliminary to demonstrate that oxygen extraction is possible.

Extraction of metals. Any process that can release oxygen from lunar materials also is producing a reduced material, e.g., metal, at the same time. For example, the hydrogen reduction of ilmenite produces metallic iron and TiO_2, and the carbothermal reduction process can produce silicon as well. Other processes, for example HF reduction and magma or molten-salt electrolysis can lead to the production of a range of metals. Although hydrogen reduction of ilmenite produces a residuum of TiO_2 and Fe^0, experimental studies of the reaction inevitably lead to Fe^0 being intimately mixed with TiO_2. In principle, a high temperature furnace at an oxygen fugacity below the ilmenite stability buffer curve could be used to heat this mixture to the melting point of iron, which could be separated from the slag. Carbon can be used to reduce silicon, as well as iron (Rosenberg et al. 1996). The iron is more readily reduced and can be extracted at lower temperature than that needed to reduce silicon. In fact, the process of producing elemental silicon is more complex, because the first product of reaction of carbon and silicon is silicon carbide. On Earth, silicon carbide in the presence of excess SiO_2 is reacted at about 1500 °C to produce elemental silicon. No complete reactor for the production of silicon by this method has been defined.

For production of elements higher on the electrochemical series, fluorine has been proposed as the reducing agent (Keller 1988; Keller and Taberaux 1991; Burt 1992; Waldron 1993). Indeed, fluorine will attack almost all constituents of lunar rocks and, by a variety of separation steps, elements or oxides could be produced. However, the process is complex, might require makeup of fluorine, which is scarce on the Moon, and could produce a great quantity of unusable products.

Magma electrolysis has also been proposed (Haskin et al. 1992). In this process, raw materials are heated to their melting temperature and metals and oxygen extracted by electrolysis. This also can in principle reduce all constituents to the elemental stage, though Fe, Si, Ti, and Al will be produced in that order. There are many technical difficulties associated with magma electrolysis, such as containment vessels and electrode stability; however, the fact that it operates at high temperature does not mean that it is overly energy intensive. The electrical energy that must be provided is the same energy that must be provided to break metal-oxygen bonds in other processes. Thermal energy can be used to heat the material to its melting point. Molten salt electrolysis, which is similar to magma electrolysis, but in which small amounts of the material to be processed are dissolved in a molten chloride or fluoride bath, may also be useful. This approach is used terrestrially for commercial production of metals such as Al and Ca, and has been proposed for production of Si (Rao 1988). A molten salt system would operate at lower temperature and would probably focus on extracting a single element, such as Si or Al from lunar anorthite. Operational problems, such as electrode stability and replacement of electrolyte, would have to be solved.

Much materials-processing research has been aimed at using regolith as the starting material. As pointed out previously, this eliminates the need for crushing or grinding of the feed material. However, the mixed chemical nature of regolith leads to the problem that either mixtures of compounds (e.g., Fe + TiO_2) that require further processing are produced, or that more material is processed than may be needed for the applications intended. One way to deal with these problems is to consider pre-processing of feedstock by chemical means. For example, lunar plagioclase might be digested in mineral acid (HCl, H_2SO_4) and relatively pure oxides (SiO_2, CaO, Al_2O_3) separated by chemical means at low temperature. The energy required for this process is principally that needed to recover the acid. Gillett (1997) has proposed a similar process in which silicates are dissolved in an acid-alcohol solution. These types of dissolutions are commonly used in preparation of silica gels for sol-gel processing in ceramic production and the intermediate products are well known. However, no research has been done to demonstrate the production and separation of the oxide phases. This type of processing would to some extent mimic the natural processes that have concentrated elements in the Earth.

If the oxides can be concentrated chemically, the chemical processing steps identified above may be more tractable. Iron oxide, separated from ilmenite, could be reduced directly with hydrogen to produce metallic iron. Silicon could be produced by carbothermal reduction of SiO_2 without the intermediate steps that involve the carbides or oxides of the other elements. Also, the oxides may be useful in their own right. Mixtures of SiO_2, CaO, and Al_2O_3 in various proportions will produce useful ceramics and cements. TiO_2 is a widely used industrial product on Earth. Chemical separation might also lead to processes for concentrating byproduct trace constituents, such as Ba or REE in plagioclase. This remains a largely uninvestigated area.

Some elements must be obtained in high purity to be useful. This is the case, for example, for Si, if it is to be used in photovoltaic devices. Silicon for these purposes must contain less than 100 ppm of contaminants. Silicon for semiconductors must be two orders of magnitude purer. On Earth, Si is purified by fractional distillation of SiF_4 in a process that requires considerable energy and is inefficient. Pre-processing of anorthite to produce SiO_2, as suggested above, may be a practical purification step in which contaminating species such as Fe and Ti can be largely eliminated.

Extraction of hydrogen and water. Hydrogen is perhaps the most important, but among the rarest, element on the Moon. It is incorporated into the regolith by solar wind implantation and exists at concentrations of 50 to 100 ppm in many regolith samples. Experiments show that the hydrogen can be extracted by heating regolith to modest temperatures (800 °C), in a process that also releases other volatile components (He, CH_4, H_2O, etc.), either from other solar wind species or from the reaction of solar wind species with oxides in the regolith (Gibson and Johnson 1971). Once released, hydrogen could be reacted with ilmenite to produce water (Allen et al. 1994b, 1996).

Eagle Engineering (1988) provided an engineering analysis of systems that would extract oxygen from lunar ilmenite by hydrogen reduction in a fluidized bed processor. Two approaches were studied. The first approach assumed that hydrogen brought from Earth would be reacted with ilmenite concentrated from the lunar regolith or from ilmenite-bearing basalt. The optimum temperature of the reaction is over 900 °C, and water has to be extracted as fast as it is formed, in order to allow the reaction to continue. This was accomplished by extracting the vapor phase through a high-temperature electrolysis cell, which produced hydrogen and oxygen. All hydrogen was returned to the reactor. In the other process studied by Eagle Engineering, a combined process whereby solar-wind hydrogen would be obtained by pyrolysis of lunar regolith and would react at the same time with regolith ilmenite. This process would produce water, from which hydrogen and oxygen would be formed by electrolysis. Figure 6.9 provides a schematic of this system, and Table 6.13 lists some of the principal characteristics of this approach, which could become economically feasible if hydrogen contents were greater than the 50 ppm assumed by Eagle Engineering.

Extraction of water from possible lunar ice deposits near the poles (e.g., Feldman et al. 2000, 2001) should be simpler and require less energy than the extraction of hydrogen and oxygen from the lunar regolith, because (a) the expected concentrations of water (~1%,

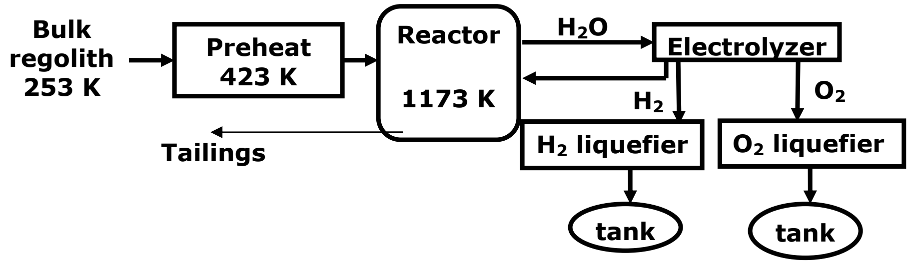


Figure 6.9. Schematic of a process to extract hydrogen from typical lunar regolith. Note the very large quantities of regolith that must be processed to extract the small amounts of H_2 and O_2. The system would have to be more complex, to deal with the other volatiles present in the lunar regolith, but these would also become useful byproducts.

Table 6.13. Characteristics of system to extract hydrogen and oxygen from lunar regolith (0.5 tonne/month LH_2; 2 tonne/month LO_2) (Eagle Engineering 1988).

System Element	*Mass (tonne)*	*Power*
Front-end loaders (3)	7.7	66 kWe
Haulers (5)	5.1	18.6 kWe
Feed and tailings bins	0.74	
H_2 extraction reactors (2)	16.6	1557kWe; 4670kWt
Other H_2 extraction eqpt.	1.1	
Electrolysis	0.1	16.8
O_2 Liquefier	0.1	1.7
H_2 Liquefier	0.1	36.3
Storage tanks	1.61	
Radiator and Thermal Control	3	48 kWt
Nuclear Power System	13	
Total	60	1611 kWe; 4670 kWt*

Note: All thermal energy was assumed to be waste heat from the nuclear reactor. kWe = kilowatts of electricity; kWt = kilowatts of thermal power.

equivalent to ~ 0.1% hydrogen) are greater than the concentration of hydrogen in the typical regolith (0.005 to 0.01% H) and (b) ice can be converted to vapor at much lower temperatures than are required for the extraction of hydrogen from the regolith. Mining in the lunar cold traps will be more difficult, perhaps, than mining elsewhere in the sunlight (Duke 1999). Extraction of water for propellant production will also lead to the production of excess oxygen, as the most energetic O/H ratio for propulsion is about 6, rather than 8 as in water. A schematic for the process is shown in Figure 6.10 and Table 6.14 estimates the characteristics of a plant to extract propellant from lunar ice. It was assumed that the ice concentration is 1% by weight and that other characteristics are scaled from the Eagle Engineering model. The principal differences are associated with the mass of regolith that needs to be processed and the lower energy to which the material must be heated. Clearly, the lunar ice extraction plant is much more productive than the one that derives hydrogen from the regolith.

<u>Sources of chemical reactants on the Moon.</u> One of the principal difficulties with chemical processing on the Moon is the need to provide chemical reactants. The amount of reactants required can be very large. Consider the reaction $Si + 4HCl \rightarrow SiCl_4 + 2H_2$. In

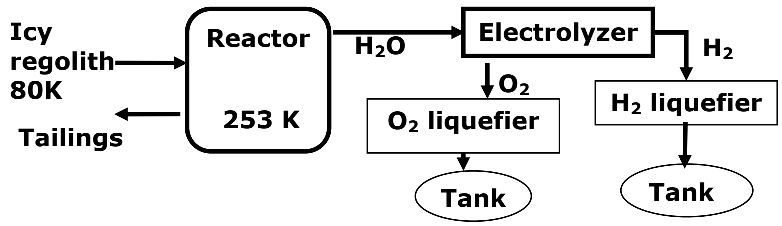


Figure 6.10. Schematic of a process to extract hydrogen from typical lunar regolith. Note the very large quantities of regolith that must be processed to extract the small amounts of H_2 and O_2. The system would have to be more complex, to deal with the other volatiles present in the lunar regolith, but these would also become useful byproducts.

Table 6.14. Conceptual plan for extracting 2.2 tonne/month of H_2 from lunar ice. For the solar power system, it is assumed that electrical power can be provided at 4kg/kW.

System Element	*Mass (tonne)*	*Power*
Front end loaders	.35	3.3
Haulers	.25	1.0
Feed and tailings bins	0.03	
H_2O extraction reactor	1.00	55.0
Other H_2O extraction eqpt.	1.10	
Electrolysis	0.10	16.8
O_2 Liquefier	0.10	1.7
H_2 Liquefier	0.10	36.3
Storage tanks	1.61	
Radiator and Thermal Control	.10	
Solar Power System	0.50	
Total	5.44	114.0

this reaction, the mass of HCl is over four times the mass of the silicon being reacted. Loss of reactants from the system is magnified with respect to production of the product. Losses can occur in several ways. Leaks of gaseous phases may occur, but systems will have to be engineered to be tight and techniques exist to isolate reacting systems from higher and lower pressure environments. The loss of reactants to unrecoverable forms may be more important. If a minor constituent reacts with HCl to form a chloride that cannot be easily recovered, this reactant will be effectively lost and will have to be replaced. This consideration drives the selection of reactions toward those for which reactants can be replaced by using indigenous lunar material. The discovery of polar hydrogen may lessen this problem; however, useful deposits of C, S, Cl and other chemical reactants remain high priorities for exploration or the development of processes to extract them from low-grade sources. The tradeoff must be made between creating a new process to extract minor constituents from the regolith and improving the design of reactors to recover the maximum amount of the reagents utilized.

4.3.6. Power for resource recovery on the Moon. Access to electrical and thermal energy is essential for inhabited facilities, scientific stations, and materials production facilities. Most of the processes required to extract basic materials on the Moon are quite energetic (e.g., Table 6.12). The requirement can be for thermal or electrical energy or both. Thermal energy can be provided by concentrated solar energy, by waste heat from nuclear sources, or by resistance heating. Photovoltaic devices, solar dynamic electrical generators, or nuclear systems can provide electrical energy.

The mass of solar photovoltaic arrays needed to produce a given power level is quite small using thin-film technologies (Tuttle et al. 2000). However, the 14-day cycle of day and night on the Moon requires that a solar-energy system include energy storage (e.g., fuel cells) for nighttime use. Fuel cells are not in themselves very massive, but the reactants needed to provide 14 days of energy supply are large. Producing these reactants on the Moon (typically H_2/O_2) would lessen the mass that must be transported. At selected near-polar sites, *nearly continuous* access to solar energy may be available to solar collectors (e.g., Bussey et al. 1999). Alternatively, nuclear reactors, which can operate continuously, will be attractive for some applications. Nuclear reactors were being designed for planetary applications in the early 1990s, but research was terminated when near term opportunities for human missions disappeared. Current NASA efforts to develop nuclear electric propulsion systems may lead also to reactors that can be used on the lunar surface. Nuclear reactors require a great deal of shielding, and will not be particularly mobile on the Moon. Lunar regolith can be used for shielding to reduce the cost of transporting radiation shielding material to the Moon.

Power at low levels has been provided in space for many years using radioisotope thermoelectric generators (RTGs) to convert heat from a radioactive source to electricity by thermoelectric conversion. Recent developments of Stirling Dynamic Isotope Power Systems (Thieme et al. 2000), which also use radioactive heat sources, have increased their efficiency of electricity production to about 25%. It may be possible to design a RTG system in which the 75% of energy generated as waste heat also can be used. These then could be competitive with other forms of energy for both fixed and mobile applications.

The production of photovoltaic cells from lunar material has been suggested by Ignatiev et al. (1998). Silicon is plentiful on the Moon. Silicon suitable for PV cells must be quite pure and techniques to purify silicon on the Moon remain to be developed. Ignatiev et al. (1998) proposed to deposit PV cells directly onto the lunar surface (as previously suggested by Criswell and Waldron 1990) by vacuum evaporation, which would eliminate the need for structural support. It might also be possible to build arrays by depositing the PV devices on lunar glass sheets, then erecting them using robotic devices. In either case, the fabrication and emplacement or erection of PV cells using lunar material could lead to very low cost power on the Moon with very little importation of material from Earth. Most needed materials exist on the Moon for producing solar concentrators, which could be used to provide thermal energy for material processing.

In cases where solar energy is tapped, energy storage can be accomplished using regenerable fuel cells, in which water is electrolyzed during the day using solar energy and the hydrogen and oxygen reacted during the night to produce electricity (Fig. 6.11). This technology is being considered for use in the DARPA "water rocket" program. In that application, water would be delivered to a spacecraft and H_2 and O_2 produced by electrolysis for use as propellant. If the water cycle were to be closed, a regenerable system would result.

Most power generation systems are more effective when centralized. Nuclear plants must be separated from other activities because of the radiation hazards that require shielding and the possibility of accidents. Solar arrays require large areas for significant power capability. Thus, it is necessary to transmit energy from central production facilities to its place of use. As on Earth, some of the energy transmission may be through the transport of chemical reactants (e.g., H_2 and O_2 pipelines). Electrical cables can be laid on the lunar surface or buried within the regolith, which is highly insulating. Over the past few years, transmission of energy by microwave or laser beams has been intensively studied in connection with the definition of solar-power satellites (e.g., Mankins 2001a). Such systems require line-of-sight

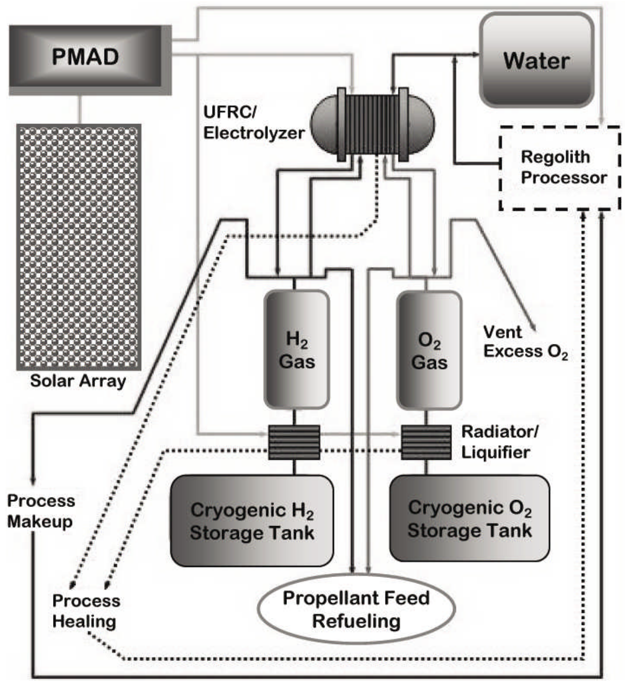


Figure 6.11. Schematic Regenerable Fuel Cell. During the day, energy from the solar array allows water (upper right) to be introduced into the electrolyzer, producing hydrogen and oxygen. At night, the process is reversed, producing energy and reconstituting the water.

communications between points on the lunar surface, but would be well suited to long-distance transmission on the Moon and perhaps particularly for work in the polar regions, where high points that are generally in sunlight lie close to and at higher altitude than points in permanent shadow (Schrunk et al. 1999), allowing creation of a lunar electrical grid.

4.3.7. Manufacturing. Propellants and H_2O and O_2 for life support are used in the form in which they are initially produced, either in liquid or gaseous form. For most other products from lunar resources that might be utilized on the Moon or in space, additional manufacturing is required. Assuming that a range of useful raw materials—metals, ceramics, glass and possibly organic materials—are available, the manufacturing techniques to be utilized will be derived from terrestrial practice. The techniques that will be favored are those that are the simplest, are tailored to the lunar environment, and can be delivered and operated at reasonable cost. The decision whether to manufacture a product on the Moon will be linked closely to the demand for the product. Products in low or intermittent demand are likely to be imported from Earth, whereas manufacturing on the Moon should be considered for products that are required consistently and in high volume.

Basic shop equipment (lathe, drill press, saws, etc., with a skilled machinist or computer controls) can be used to manufacture a wide variety of objects and even new machines. The earliest lunar outpost should include a well-equipped machine shop. In the past two decades, great advances have been made in integrating information systems with manufacturing (e.g., rapid prototyping approaches, numerically controlled machines), which increases the versatility of the manufacturing system and may be able to produce a variety of useful products with the same equipment. This approach may make it feasible to locally produce items that may be required on a more rapid timescale than can be accommodated with resupply from Earth. Consideration should be given to emphasizing the production of machine tools, e.g., drill bits, from lunar materials early in a lunar outpost program. The lunar surface offers an environment in which advanced techniques, such as laser drilling or cutting, might be applied.

Some manufacturing techniques will make beneficial use of the lunar environment. The production of silicon PV devices (Ignatiev et al. 1998) is one example, which uses the lunar vacuum and incident solar radiation in the manufacturing process. In their technique, elemental silicon (and other materials) is deposited by vacuum evaporation onto a surface of glass made by fusing lunar regolith. Thus, mechanical steps of manufacturing, such as cutting and forming are largely bypassed. Perhaps more complex vacuum evaporation techniques can be used to form three-dimensional objects.

Allen et al. (1992, 1994a) demonstrated that bricks can be manufactured by sintering regolith into compact, dense and strong forms. This process could be readily added to an extraction system that requires heating of regolith to high temperature. Mare regolith must be heated to 1000-1100 °C to sinter properly. This is somewhat above the reaction temperatures for reduction of ilmenite (900 °C) or extraction of volatiles from lunar regolith (800 °C), but it should be possible to add heat at the appropriate step in the process so that bricks can be formed. These may retain porosity if cast under surface conditions; however, pressing the bricks can densify them.

Taylor and Meek (2004, 2005) have discovered a unique property of lunar regolith/soil that presents significant potential for microwave processing. The nanophase Fe^0 present throughout the soil, associated with the abundant glass, strongly absorbs microwave radiation. Samples of lunar soil (not simulants as in previous studies) placed in a normal kitchen microwave (2.45 GHz) completely melt within a few minutes, "almost before the tea water comes to a boil." The temperatures generated by this radiation on the lunar soil is on the order of 1200–1500 °C. Microwave processing may be an effective method for releasing solar-wind implanted gases in lunar soil or heating regolith at the poles to facilitate the recovery of water. However, the energy efficiency of the process has not been investigated. Microwave sintering of regolith may be useful for paving roads (Taylor and Meek 2005), or producing bricks, structures, even antenna dishes.

Cast basalt has been used in Europe for manufacturing sewer pipes (e.g., Jakes 2000) and a wide variety of products might be produced in this manner. Molds could be constructed of mineral fragments sieved from the regolith. Anorthosite regolith sand might be a useful molding material for molten basalt. Heating could be provided by microwave, solar or waste energy from nuclear reactors.

Production of objects of specific shape and composition will be quite useful. Duke (2000) suggested that a process known as "combustion synthesis" could be used for fabricating near-net-shape objects (Moore and Feng 1995). Combustion synthesis is a process in which a mixture of solid reactants that undergo a strong exothermic reaction once ignited is formed into the desired shape. When the mixture is ignited, it can react to completion without additional energy input. Reactions are typically rapid (seconds). In cases where the reaction products are also solid, the process can be carried out in a vacuum environment. Among the products that might be made in this manner are glasses (e.g., formed by the reaction of CaO, Al_2O_3, and SiO_2 in appropriate mixture), glass-ceramics, intermetallic compounds (Fe-Ti), or ceramics (Al_2TiO_5).

Freitas and Gilbreath (1982) surveyed a wide variety of materials-processing and manufacturing techniques that might be applicable to manufacturing with lunar materials, particularly for structural materials and other solid forms. For working with metals, traditional casting, rolling, extrusion, powder metallurgy, and other techniques may be useful for manufacturing a wide variety of shapes ranging from bars to wires to pipes. In these cases, terrestrial technology may have to be adapted to the smaller throughputs expected for lunar manufacturing and the need to operate in the lunar environment. Joining techniques for use in the space environment will need to be developed that are suitable for the materials and thermal characteristics of the environment.

Many of the products now used in everyday life are based on organic materials, which are likely to be in short supply on the Moon. Carbon and nitrogen compounds will be the subjects of intense conservation on the Moon. Planning of materials to be brought from Earth should recognize the secondary value of these materials on the Moon, so that substitutions might be made on Earth where materials such as carbon-epoxy can be used in place of metallic constituents. A carbon-epoxy recycling system remains to be developed.

4.4. Uses of lunar resources

There are many ways in which lunar resources can be used in an exploration and development strategy. The principal rationale in the early phase of development would be to offset costs of transporting needed equipment, materials and supplies from the Earth to the Moon. In a second phase, the emphasis would move toward providing consumables for lunar outpost crews and exportation of goods, particularly propellant, from the Moon. In the third phase, emphasis would turn toward self-sufficiency, enhanced exports, and new services for Moon, space and Earth.

4.4.1. Propellant. With current technology, the only way in which payloads can be landed on or launched from planetary surfaces is through the use of rocket engines. Although it is possible to launch payloads from airless bodies (it has even been proposed for Earth) using electromagnetic launchers, the low accelerations that can be withstood by humans makes the establishment of an electromagnetic launcher a daunting engineering task, owing to the long acceleration distances needed. In space, more efficient means of propulsion will be developed; however, these still require propellant, only in smaller quantities with respect to payloads. For a very long time, propellant will be a valuable product in space. Propellants potentially come in many forms. Hydrogen and oxygen are the most efficient choice for rockets. Hydrogen is used in nuclear propulsion systems, though techniques for augmenting hydrogen with oxygen have been investigated (Borowski et al. 2002). Electric propulsion vehicles work best with high-mass inert gases, such as Xe, which is not likely to be produced soon outside of Earth. The most logical choice of propellants in the next few decades would be hydrogen and oxygen, for transportation in near-Earth space and for Mars missions. Hydrogen, however, requires very low temperatures for liquefaction, is low in density (requiring large tanks), and is prone to loss. Therefore, alternate fuels (e.g., methane) or forms of storage should be considered.

The demand for propellants in space is significant. Within the next few years, approximately 500 mt of propellant will be utilized annually in low Earth orbit to send communications satellites to GEO. Of course, current launch systems do not stop in LEO to refuel, so the propellant is carried on board the vehicle as it is launched from Earth. However, this use could provide a market for propellant from the Moon if the cost of lunar propellant in LEO became less than the cost of propellant transported from Earth. Blair et al. (2002) analyzed the commercial prospects for lunar propellant. To this potential market could be added military satellites, government, lunar, and Mars human exploration and development missions, and satellite servicing requirements. Nock et al (2003) described a Mars exploration architecture using cycling spacecraft between the Earth and Mars, which utilizes lunar propellant.

4.4.2. Power. Power is central to any human activities on the Moon. Presently, for a process that requires 20 kW/kg to produce (e.g., metals), the mass of the power system that must be provided is 50–80% of the total production system mass. Providing power from local resources offsets a need to import massive systems from Earth. Materials used in the collection and distribution of energy are among the most useful products that could be manufactured from lunar materials. The major constituents of photovoltaic devices are readily available on the Moon. Also, once power systems can be produced from lunar materials, the lunar outpost will be capable of expanding its own power supply, one of the principal determinants of growth rate for a lunar establishment.

If the engineering of fusion power plants burning ^3He is accomplished, the Moon is the closest and most likely point of supply. The process of extracting ^3He for use on Earth would also release immense quantities of H_2 and O_2 for use as propellant or life support consumables.

4.4.3. Life support consumables. Water, oxygen, and nitrogen (or argon) are the principal "consumables" required for people to live and work in space. The term "consumables" is in quotation marks because in space, it will be important to recycle these constituents and to lose as little as possible. The ability to produce consumables from lunar resources has two major effects. The first is to offset the need to transport them from the Earth. The second, and perhaps more important, is that they provide the opportunity to build reserve caches that would otherwise be too expensive to provide. These reserves would make a lunar outpost life support system more robust against accidental losses of consumables and could alter the way in which a human crew conducts daily life. Inert atmospheric gas to maintain breathable environments is the most difficult provision to supply from the Moon. The only known source is the solar-wind-implanted nitrogen in the regolith and small amounts of argon from solar wind and internal sources implanted in grains in the lunar regolith.

Life support systems for lunar outposts will be highly conservative of their materials. Everything possible will be recycled. Production of food at the outpost can relieve a considerable burden on the Earth-Moon transportation system and will be a key research, development, and operational activity at any outpost. If transportation costs between the Moon and LEO become much less than Earth to LEO, it may become profitable to grow food on the Moon for export to LEO, recycling organic wastes generated on Earth-orbiting stations. Addition of C, N, and H obtained on the Moon to the life support system could be used to increase the robustness of the outpost by making up losses and increasing the stored reserves. However, in terms of masses of materials required, the requirements for life support will be far smaller than requirements for propellant.

4.4.4. Construction materials. Construction materials may be utilized to build habitats and work areas. These could be in the form of metals, such as iron, or ceramics and glasses formed from silicate minerals. At an advanced stage of development with low energy costs, metallic aluminum may be produced for structural use. These same materials could be used for ducts, pipes, wires, etc. Bare metal wires may be sufficient for external use if buried in regolith. Internal wiring will be brought from Earth until practical means of producing insulating materials from lunar materials are developed.

If water is readily available, concrete made from lunar material may be useful in a variety of applications (e.g., Lin 1987). Calcium and aluminum oxides are constituents of plagioclase feldspar, which is ubiquitous on the Moon's surface, and could be residual to processes that produce Si from plagioclase. In appropriate mixtures, CaO and Al_2O_3 could be mixed with graded sand, mechanically separated from the regolith, and rock fragments to produce concrete. Concrete could have many uses, from building structures to holding tanks for water. Concrete could provide a basis for constructing pressurized habitats from lunar materials.

Structural materials might be formed by sintering of the regolith (Allen et al. 1994a) or by melting basalt (Jakes 1999). Sintered regolith might be a byproduct of high-temperature processes that extract volatiles or oxygen from lunar regolith. Aggregate derived from regolith processing will be useful in stabilizing roadways and work areas.

4.4.5. Manufactured products. A wide range of manufactured products can be conceived from lunar materials. These include items ranging from storage tanks for fluids to a wide range of other items (such as furniture or utensils). At an early lunar outpost, some of the time a crew spends will be aimed at broadening understanding of what products would be most useful. If useful manufactured items can be produced, they may be candidates for export to other locations in space. Major construction projects in space have been suggested. The largest of these would be solar-power satellite systems, each of which would require 50,000 mt of material and might be built at the rate of one per year (Mankins 2001a). If supplied from the Moon, this would also require the production of similar amounts of propellant (although electromagnetic launch is possible for inert materials). Therefore, if this type of project were to be developed, substantially larger amounts of materials would be required than the current requirements for propellants in space, and the demand could drive the development of a broad industrial capability on the Moon.

4.5. Economics of lunar resource utilization

The foregoing description outlines the availability of resources on the Moon and the approaches to their development. What is technically possible is not necessarily economically feasible. In order to determine what lunar resources should be developed and when, some level of economic justification will be required. This justification could range from saving cost (or decreasing risk) on a particular mission or program to demonstrating a new profitable industry in space. In general, the economic benefits from lunar resource utilization will be greatest on the Moon, as the lunar surface is the place with the highest transportation costs from Earth. Exporting products from the Moon to near-Earth space faces a steeper economic barrier because of added transportation costs from the Moon and smaller transportation costs from Earth. The cost associated with a lunar product will also increase with the complexity of the process to produce it. Using lunar regolith for shielding requires minimal processing, whereas producing solar cells from lunar materials requires excavation, extraction, surface transportation and manufacturing steps and will be more expensive to develop. The other side of the equation is the volume of the demand for the product. If the investment in developing the process can be distributed across a large amount of product, the economic feasibility will be much more likely than if there are only a few uses of small amounts of material. For these reasons, the production of propellant and life support consumables appears to be the most likely choice for early development of lunar resources. Propellant is required in rather large amounts (for some applications, customers already exist), the processes involved are not overly complex, and the materials are relatively easy to handle. In addition, as discussed previously, production of propellant on the Moon can reduce the transportation cost of emplacing other production equipment on the Moon.

Development of an indigenous energy supply is the second most productive early development. If means can be demonstrated to produce solar photovoltaic cells or solar thermal concentration systems from lunar materials (at competitive costs to bringing the systems from Earth), the cost associated with developing additional production systems can be reduced. Development of an indigenous energy supply on the Moon can reduce the cost of exporting products to space.

In principle, it would be possible for a largely self-sufficient settlement, capable of expanding its facilities using indigenous materials, to be established on the Moon. It would have to use intensive recycling and might be limited by supplies of volatiles, such as nitrogen, carbon and hydrogen. However, if lunar materials can be economically exported to space, the basis for a separate lunar economy could be established, supporting the possibilities for economic self-sufficiency for lunar operations.

4.5.1. A case study of the economic use of lunar resources. Blair et al. (2002) examined a scenario in which propellant is derived from icy regolith in shadowed craters near the lunar poles. The customer for the propellant is a space transportation system based at Earth-Moon L-1, which uses a space-based orbital transfer vehicle to bring communications satellites from low Earth orbit to GEO. This is a current commercial market opportunity with a target of about 30 communications satellites bound for GEO per year with an average mass of 5 mt.

The average transportation cost for these satellites is approximately $100 million per launch. Seventy percent of this cost is associated with carrying the satellites between LEO to GEO, and 30% with launching them from Earth. This means that there is a potential customer base for transporting payloads from LEO to GEO, equivalent to approximately $3.5 billion per year. If lunar propellant becomes less expensive in LEO than propellant brought from Earth, some or all of this market might be captured.

The Blair et al. (2002) space transportation system is designed to fly from L-1 to LEO, rendezvous with a communication satellite delivered by a much smaller rocket to LEO, carry the satellite to GEO, then return to L-1 for refueling and another trip. In this analysis, the production system on the Moon was designed, including the ice excavation and mining system, water extraction, electrolysis and liquefaction of propellant on the Moon. Only enough water is electrolyzed on the Moon to provide propellant for a lunar water tanker to fly to L-1 and return empty to the Moon. The tanker carries water to L-1, where another electrolyzer produces propellant for the operation of the orbital transfer vehicle. L-1 is a good location for this transportation system because it is straightforward to fly to any Earth orbit with about the same energy requirement. Aerobraking is used to decelerate the orbital transfer vehicle in the Earth's atmosphere.

The analysis considered a number of factors, including the research and development costs, the cost of producing all of the hardware, costs of operations (modeled as an annual refurbishment cost of lunar systems, the propellant depot, the lunar tanker, and the orbital transfer vehicle), the concentration of ice in the lunar deposits, and a number of economic variables such as the rate of market capture, discount rate, and financing approach. The lunar production facility was emplaced with a series of identical segments, which allows propellant produced in early phases of development to be utilized in transporting the remainder of the system to the Moon. This "bootstrapping" technique is effective for the same reasons that were defined in Section 3.0, as the burden of launching hardware from Earth is substantially diminished.

The Blair et al. (2002) analysis concluded that, while the performance of the lunar propellant production facility (measured in terms of the amount of mass that would have to be launched from Earth to LEO) was excellent, it was not clear that a commercial organization could afford to develop the capability. If the research and development costs were to be borne by a government organization (this is perhaps reasonable for basic infrastructure technology development), the scenario approached economic viability. However, to be completely viable as an investment opportunity, a number of developments would be needed, including improved technology for excavation and extraction, exploration for higher concentrations of ice, and development of technology for operating in permanently shadowed areas. These likely would have to be supported by government as part of an exploration program. It was also shown that a larger market for propellant would be beneficial to economic feasibility.

4.5.2. Strategic considerations and priorities for lunar resource development. As shown in Table 6.15, several strategies may be important in developing economically competitive lunar resources.

"Bootstrapping" is a strategy that can be applied to the development of the Moon. Bootstrapping, as defined by Criswell (1978) means using indigenous materials to produce machines, which then produce the desired products. Machines could include mining, beneficiation, extraction and manufacturing machines. It is not necessary that entire machines be produced from lunar materials. If the massive parts (e.g., iron pedestals for heavy machines or insulation for high temperature furnaces) can be made from lunar materials, significant reductions in transportation costs may be achieved. As the capability for manufacturing items from lunar materials grows, the lunar outpost can approach self-sufficiency and can begin to expand based primarily on resources from the Moon.

Table 6.15. Strategic considerations for the development of economically competitive lunar resources.

Strategy	***Approach***	***Utility***
Produce propellants	Extraction from water at poles or from regolith or volatiles from the regolith	Reduces cost of transportation for outpost operations or expansion
Lower energy costs	Produce portions of or entire energy collection systems from lunar materials	Easier to recover lower-grade mineral deposits; expand capabilities to produce metals, other materials with large energy requirements
Beneficially use lunar water	Extract water from cold traps or from regolith	Propellant, life support; Enable new processes based on availability of water (e.g. leaching trace elements from regolith)
Utilize regolith rather than rock	Extract products from fine-grained regolith rather than from rock	Uses natural processes of impact for comminution, bypassing need for additional energy for rock crushing
Simple beneficiation	Size classification; magnetic susceptibility and electrostatic separations	Beneficiation increases concentration of useful constituents in processed materials (e.g. solar wind hydrogen concentrated in <20 µm fraction; reduce process energy by size separation; concentrate metallic iron (Taylor and Oder 1990) or ilmenite (Agosto 1985) in regolith
Throw nothing away.	Keep track of residuals in processed materials	Decomposition of anorthite as a source of SiO_2 for production of silicon. Use byproduct CaO, Al_2O_3 and Na_2O; Extraction of ^3He from lunar regolith produces ^4He, H_2O, C, N (Kulcinski et al.1989).
Recycle everything.	Design for reuse; inventory materials; recover organic wastes	Reduces imported materials and energy requirements

The development of lunar resources might be undertaken only for economic reasons; however, government programs such as the human exploration of Mars or the establishment of astronomical observatories could precede the economic development of the Moon and benefit from lunar resources. Such scenarios would be attractive to commercial investors, because governments would bear much of the cost of infrastructure development. Assuming such a government-led strategy, Table 6.16 identifies two categories: Category A includes those resource development concepts that can significantly reduce the cost and increase the robustness of a lunar outpost development strategy; Category B includes developments that can increase the robustness and safety of operations on the lunar surface and provide additional products for local use or export.

4.6. Status of U.S. and international space resource law

International space law has been viewed as a potential barrier to lunar resource development. Viikari (2003) has compared the legal regimes required by current international treaties (The Outer Space Treaty, which most countries have agreed to, and the Moon Treaty, which has not been adopted by any of the space-faring nations) and the Law of the Sea. The Outer Space Treaty contains provisions that provide for freedom of exploration, but prohibit national appropriation of an object in outer space, and calls for the avoidance of harmful

Table 6.16. Categorization of utility of use of lunar resources in a lunar outpost program.

Category A: Reductions in cost of a lunar outpost	*Category B: Upgraded capabilities and products.*
1. Propellant and life support—H_2 and O_2.	1. Sintered regolith materials for construction of roadways, launch and landing facilities, shielding—bulk regolith.
2. Power production and distribution systems—Si for PV devices, metallic iron for conductors and wires.	2. Machine replacement parts for mining and materials processing—iron alloys, ceramics.
3. Glass and ceramics for structural material—silicates and oxides.	3. Alloying elements for more complex manufactured products; requires additional lunar exploration

contamination. Further, nations are responsible for what they or their citizens do in outer space. These provide a starting place for the establishment of rules that could pertain to resource development on the Moon, but are as yet too general for direct application. Viikari discusses how the Law of the Sea has been developed to include mechanisms that would allow economic utilization of seabed resources. Although rather complex, these mechanisms could be adapted to the case of lunar resources. The Moon Treaty of 1979 raised more questions, particularly because it stressed the concept of the Moon's resources being the common heritage of mankind. This treaty was seen as being an impediment to lunar resource development and, consequently, the United States, Russia and other space-faring nations have not ratified it.

These observations suggest that certain international legal considerations could emerge if a project for the extraction and utilization of lunar resources were to be undertaken by a government or private group (which would have to operate under license to a government) (Schmitt 1997). Although the Space Treaty prohibits the national appropriation of the Moon or of a particular location on the Moon, the Treaty does not prohibit the extraction of materials from the Moon (Sterns and Tennen 2003). Although this would appear to exclude private ownership of resource deposits on the Moon, there are well-established mechanisms for private enterprise to extract resources in the absence of land ownership, such as grazing leases on public lands and off-shore oil platforms (Sterns and Tennen 2003). Compliance with the Treaty's guidelines by a legal corporate entity under the laws of the United States can be straightforward provided the government chooses to be enabling rather that inhibiting (Schmitt 1997).

On the other hand, if the Moon Treaty were to be ratified by major space-faring nations, a high degree of uncertainty that is antithetical to private commercial activities on the Moon would result (Schmitt 1998). The Agreement could, create a de facto moratorium on such activities. A mandated international regime would both complicate private commercial efforts and establish international political control over the permissibility, timing, and management of all commercial resource activities.

The general status of the U.S. government's regulatory involvement in space related activities has no known or foreseen road blocks to an all private lunar resource initiative. Many regulatory hurdles must be overcome, however, none have proved insurmountable for existing private entities involved in commercial endeavors involving launch, communications, remote sensing, biomedical research, and space services activities. The same conclusion can be made for current tax law, although such law certainly could be made more encouraging of all new business initiatives (Schmitt 1998).

If a private organization were to propose the development of a lunar resource and perform outside of reasonable norms, would there be any recourse by the government or the international community? First of all, the licensing nation can withdraw its launch, communications, and return licenses for cause and enforce compliance before they are re-activated. If the licensing state does not act to force compliance, the world community can bring the matter to the World Court and/or join in part or in whole to enforce sanctions against the offending entity and licensing state. Any one of these actions would have a serious impact on the private entity's ability to maintain its space operations, other than those related to safety of personnel, or its access to the capital and customer markets upon which its ability to do business depends (Schmitt 1998).

Although some uncertainty remains in the application of international law to the development of lunar resources, it appears that the international legal community has ample precedents to use in crafting a satisfactory set of regulations that would allow commercial resource development, extraction, and use.

5. THE LUNAR ENVIRONMENT

Although it is not our intention to address the topic of the lunar environment at length, it is worth a brief summary here. Preservation of the lunar environment is a cross-cutting theme that must be considered at any level of exploration or development significantly beyond that undertaken by Apollo. Many of the unique uses of the Moon are dependent on preserving its existing environment. For example, the use of optical telescopes on the Moon would be degraded if a significantly greater lunar atmosphere was created by human activities. The lunar atmosphere was modified by the Apollo landings, and effects were detectable for several months after the landings (Johnson et al. 1972). Use of the Moon's vacuum for fabrication would also be impeded if the atmosphere were to become contaminated. Volatile constituents released into the atmosphere can be condensed onto the surface or lost from the Moon. Apollo experiments measured the daytime and nighttime lunar atmosphere's concentration of natural species (e.g., Hoffman et al. 1973; see also Stern 1999). Vondrak (1989) suggested that intense human activities could lead to a permanent lunar atmosphere, but only at very high levels of effort such as those associated with ^{3}He mining. Thus, understanding of atmospheric dynamics and composition should be undertaken before human exploration becomes a continuous activity. Active experiments in which known quantities of gases are released into the atmosphere at different times of the lunar day and their fate is followed by surface instruments are required to understand the potential effects of gases released by human activities.

In addition, unique features of the Moon can be altered by incautious human contamination of the lunar environment. The unique implantation effects of the solar wind can become contaminated if additional gases with different isotopic compositions become the prevalent molecules in the lunar atmosphere. These molecules would be available for implantation in the lunar surface by ionization and acceleration in the solar wind. Thus, large-scale utilization of the Moon should be preceded by a thorough review of these effects, additional study of the implantation processes, and preservation of areas of regolith for future studies.

The lunar polar cold traps have been collecting a range of naturally released volatiles over the past several billion years. They would be subject to contamination by increased human activities. It would be prudent to study the cold trap deposits in detail before committing to intensive human exploration or development. The rates of deposition of various volatile species (including metallic species such as Na and Hg) in the cold traps should be established early in a program of lunar exploration, because they may become more difficult to establish when human activity begins.

The use of the Moon's far side for radiotelescopes has been suggested as a means of excluding intense radiofrequency contamination from Earth and other natural sources. These uses could be impeded by the presence of artificial sources in lunar orbit. The International Academy of Astronautics has commissioned a study of this issue (Maccone 2001).

Some people will be opposed to the notion of disturbing the Moon's surface for any reason, particularly economic reasons. The repair of surface disruptions will occur only at timescales of billions of years, so commitment to a surface project that alters the lunar surface should be carefully considered. Most lunar activities that can now be imagined occur at scales that cannot be observed from Earth even with large telescopes. Mining of ^{3}He is a potential exception, because very large surface areas of the Moon would be disrupted. The lunar power system concept of Criswell and Waldron (1990) would also be constructed at a scale large enough to be seen from Earth. The environmental issues associated with these very large scale project should be considered and discussed, within the same kind of framework in which environmental decisions are now made on Earth, including consideration of the economic benefits to be gained by the project.

The Outer Space Treaty prohibits adverse changes or harmful contamination of the lunar environment caused by national (or private) activities on the Moon. However, the terms "adverse changes" and "harmful contamination" are not defined (Viikari 2003) and will certainly appear differently to different parties. Thus, the basis exists for international litigation or the development of more precise language in a new treaty. Establishment of international standards probably will not occur until lunar development is imminent.

6. HUMANS ON THE MOON: ESTABLISHMENT OF LUNAR OUTPOSTS

NASA has sponsored studies of lunar outposts since the mid-1980s, and many articles have appeared in the literature (e.g., see papers in Mendell 1985, 1989; Eckart 1999) describing the functions and architecture of such facilities. Recently, NASA has been directed to develop a lunar exploration program that would lead to a human lunar outpost in 2020, as part of a long term strategy that would lead to human exploration of Mars. The major goals of the lunar program are to conduct new scientific investigations and develop technologies, including those needed to use lunar resources in support of sustainable human exploration. Thus, the major premises of the introduction to this chapter have been incorporated into NASA's planning for lunar exploration. The detailed design of the exploration and development strategy have not been defined. However, NASA, most likely in collaboration with international space agencies, will be developing concepts for the design of a multipurpose lunar outpost.

H. H. Koelle and his students have conducted long-term studies of lunar outposts (e.g., Koelle 1996) and they have categorized the functions of a lunar outpost (Table 6.17). The specific systems developed to meet these functional requirements will be the subject of lively debate for several years. The depth and breadth of the program will depend on a complex interplay of requirements, costs, and capabilities. However, there is no doubt that the facilities needed to undertake these activities could be developed within the next 15 years. There remain questions of detail, some of which have been identified in previous sections of this chapter.

6.1. Site selection for a lunar outpost

The question of where a permanent outpost on the Moon should be located is a central issue in the exploration strategy for the Moon. The selection of a site or sites for lunar outposts will be based on the intended uses of the outposts as well as operational issues such as safety of landing and return, energy availability, etc. Workshops held in 1988-1989 addressed the question of site selection for a lunar outpost, based on information available at that time (NASA 1990; Taylor and Taylor 2000). Those studies selected six candidate sites and held a mock site selection debate in which the merits of the sites were discussed by members of the science community (Table 6.18). At present, with somewhat more interest in the possible use of lunar resources, a polar site might acquire higher priority.

Table 6.17. Functions of a Lunar Outpost (after Koelle 1996).

Lunar Science and Technology	
• Research laboratories	• Mobile research systems
• Observatories	• Component subsystem and system test facilities
Production of Raw Materials	
• Mining and beneficiation	• Production of gases, raw materials and feedstock
• Production of metals	• Production of non-metallic products
Manufacturing of end products and services (for use on Moon and for export)	
• Structural components	• Assembly of parts and subsystems
• Food production	• Collection/ conversion of energy
• Other manufactured products	• Services for external customers (e.g. waste recycling)
• Propellant production	• Tourism
Direct Support Operations	
• Supervision and control	• Communication services and data management
• Health and recreation	• Space transportation services (e.g. launch services)
• Training and education	• Surface transportation
• Housing	• Construction, maintenance, repair
• Storage	• Electric and thermal power supply
	• Life Support and waste recycling

Table 6.18. Criteria for selecting lunar outpost sites (adapted from NASA 1990). The site workshops conducted by NASA established criteria for selection of scientifically useful sites.

Criterion	***Rationale***
Scientific	
For astronomy, locations near (behind) the limb and near the equator	Access to both celestial hemispheres; hidden from Earth
For geology, locations near a mare-highlands boundary	Access to widest range of general problems
For resource extraction, a mare site	Greatest flexibility
For large arrays and observatories, large flat areas	Ease of construction
Avoidance of high indigenous radiation	Possible criterion for some uses
Operational	
For safety, large relatively flat areas	Minimal problem with launch and landing
For space transportation – equatorial, polar and near side mid latitudes preferred; far side mid-latitudes avoided	Minimize propellant and timing of launch and landing restrictions
Availability of long range surface mobility	Allows selection of “safe” sites and surface traverses to interesting sites

Six sites were examined in the 1988 studies. The overall rankings of sites in that study were based largely on ability to meet scientific requirements, with somewhat greater priority given to geology, reflecting a greater variety of evaluation criteria in that area. Resource availability was not given high priority. The participants in the study were focused on developing a process, not defining the best outpost site, and concluded that none of the candidate sites could be ruled out at the time of the study from scientific and resource perspectives. For a renewed program of lunar exploration, establishment of a focused set of goals and objectives of the program will lead to a new set of site-selection criteria and renewed discussions.

If polar resources are demonstrated to provide strong rationale for a lunar outpost, further work at site definition and selection will be required. The lunar poles were suggested as lunar outpost sites by Green (1978) and Burke (1989), and have received greater attention recently due to the discovery of hydrogen concentrations near the poles by Lunar Prospector, which suggests that extractable quantities of hydrogen or water exist there.

Some of the other attributes of a lunar polar outpost site could include:

- The lunar poles, particularly in conjunction with a L-1 or L-2 space depot, can be reached routinely. For sites within 5° of the poles, continuous access is possible. Spacecraft can be launched from the International Space Station every 6 to 11 days and return at similar intervals. The minimum round trip duration is 21 days, with about 10 days spent on the lunar surface. Shorter round trip times can be accomplished if Apollo-type trajectories are used (no Earth orbit rendezvous); however, these may not be consistent with a highly reusable transportation system.
- Near the poles, it may be possible to find suitable sites where nearly continuous access to sunlight is possible. "Peaks of eternal light" (Bussey et al. 1999) will provide unusual lighting conditions that require energy management, but the sun will always be low on the horizon, so midday temperatures will be moderate. (Apollo missions were carried out in the early morning to avoid extreme noon-time temperatures). The Moon's slow rotation will cause surface shadow patterns to change slowly. Thermal variation is more modest than at the equator. Because the angle of the sun is always low, regolith temperatures are also low. Radiators can be aimed away from hot surfaces for maximum effectiveness.
- Geoscience at a polar site would primarily be focused on early crustal development. There are few mare basalt units near the poles, although access to cryptomaria might be possible. As surface transportation capability improves to 500 km sorties, access to mare sites becomes feasible. Near the Earth-facing side North Pole, intensive study of Imbrium Basin KREEP ejecta would be possible. Near the front side South Pole, similar studies of South Pole–Aitken Basin ejecta could be undertaken.
- Detailed understanding of the origin, scientific significance, and economic importance of polar hydrogen concentrations would be a primary objective. Access to lunar hydrogen will be utilized to produce lunar propellant. In the early stages, propellant will be provided on the surface. Later, propellant could be delivered to the L-1 or L-2 facility to establish a refueling station there.
- The lunar polar station can have access to the far side for astronomical observations that are hampered by noise from the Earth. This was one criterion that was accepted as important in the 1988 study, although the preferred sites were equatorial limb sites. If optical or infrared astronomy were to be a program element, a lunar polar site would be hampered by having access only to one hemisphere of the sky. A southern polar location might be preferred, if only one celestial hemisphere could be observed (NASA 1990).

- The polar outpost could allow observation of the Earth's magnetosphere (Freeman 1990).
- Technology development would focus on human support for long duration stays in an environment that to some extent mimics that of the Martian surface (low surface temperatures, low atmospheric pressure, dust, possibility of ice deposits, etc.).
- The lunar South Pole lies within the South Pole–Aitken Basin, an important and enigmatic ancient lunar impact basin. Both the North and South Poles lie within lunar highlands terrain.
- Hydrogen or water deposits near the poles may be accessible, providing an economic incentive to lunar development.

Locations near the lunar poles could provide challenging environmental problems for operations. Figure 6.12 shows a flat-floored crater near the larger crater Newton on the lunar near side, at 79°S latitude. The flat deposit on the floor of the crater may consist of mare basalt flows or impact ejecta. The pole-facing crater wall appears to be in permanent shadow, and the shadow extends at least 10 km onto the flat floor of the crater. The Earth will be above the horizon, bobbing up and down throughout the month. Astronauts working on the sunlit surface would encounter surfaces that are hot (rocks with faces perpendicular to the sun will have temperatures of about 100 °C) and very cold (less than −100 °C in shadow), as were encountered on Apollo missions, which flew to within 30° of the lunar equator. Boulders on the surface will cast long shadows, and the shadows will move throughout the month, so both nighttime and eclipse temperature changes will have to be accounted for in designing surface systems. The image of Figure 6.12 was taken by Clementine during lunar winter, when daytime shadows are the longest. The permanent shadow occupies significantly less area. For an outpost located outside of the noontime shadow throughout the year, it will be located 8 to 10 km from the minimum, permanent shadow, based on the difference between solar illumination angles in winter and summer. Initial investigations of the cold trap can be carried out during South Pole summer. Lunar Prospector data have not demonstrated that there is ice in the permanent shadow of this crater, but if ice were present, the flat-floored aspect of this crater could reduce the difficulty of extractive operations.

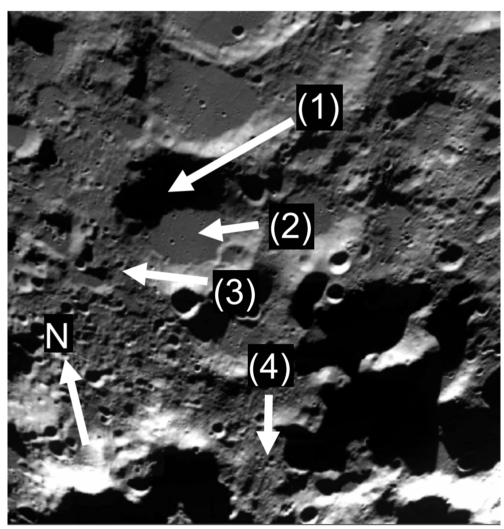


Figure 6.12. Flat-floored crater near the lunar south pole (Clementine image, UVVIS UI80S345). The north rim of the crater appears to be in permanent shadow and may be a location where ice exists. Numbers and arrows refer to potential locations of major facilities that could be associated with a polar lunar outpost at this site (see text, Section 6.1).

Figure 6.12 also shows the potential location of major facilities that could be associated with a polar lunar outpost at this site near Newton crater. These include: (1) Permanently-shadowed hydrogen mine; (2) outpost and possible mare regolith processing facility; (3) highlands material processing facility; (4) farside astronomical observatory, located approximately 600 km from the outpost, on the other side of the

South Pole. This facility could also become a regional outpost to support investigations of the South Pole–Aitken basin. Field camps and shelters might be located at 200 km intervals along repeatedly used surface transportation routes.

6.2. Surface accessibility options for lunar exploration and development

Some scientific and resource development objectives require access to distributed locations on the Moon. As the specific sites currently are unknown, this is equivalent to requiring global access, the ability to conduct either short or long duration activities at any point on the Moon. Other objectives will be well suited to a single location on the Moon, where supporting systems can be accumulated for efficiency and robustness. These two modes can be in conflict if limited resources are available. Ten sortie missions to explore diverse geological terrain might be equivalent in expense to the same number of missions that develop a robust permanent outpost. In order to help assess the tradeoffs in exploration and development strategies, Table 6.19 compares several ways in which global access might be accomplished.

For any expected long-term utilization of the Moon for science, resource extraction or other reasons, a surface transportation system should be strongly considered. The effectiveness of a surface transportation network increases with the frequency the route is traveled. Surface transportation may be used between a central outpost and a resource mining location or a remote observatory, whereas a small lunar hopper propelled by lunar resources may be most effective for conducting sample-return missions from a large number of sites. Thus, both types of systems may find use. Both will benefit from the creation of a surface infrastructure for propellant production, maintenance, and operations.

7. A STRATEGY FOR EXPLORING AND DEVELOPING THE MOON

To make effective use of the Moon for humanity, a strategic approach to its exploration and utilization should be defined, which provides scientific and technological value at each step, but also maximizes the long-term potential of the Moon. Several themes can be identified that should be addressed in the strategy; however, the priorities will depend on a variety of considerations that cannot be specified now.

Typical planetary exploration programs have been based on an iterative strategy, in which information from one mission is utilized to define the objectives of subsequent missions. Because robotic missions typically require development times of 3-5 years, these approaches tend to be ponderous, insuring long periods of time between missions. The presence of humans can alter that strategy to the extent that on-site observations and immediate feedback into exploration plans can accelerate the rate of advancement of science and technology. In developing a strategy for the Moon, attention should be given to exploration and development strategies that consider alternative pathways based on potential discoveries and that allow for rapid incorporations of new information into the mission planning activity.

A plan for exploring and utilizing the Moon should address the key scientific questions while developing practical applications. The precise mix of robotic and human elements in the exploration strategy will be dependent upon the anticipated return from lunar exploration and development. Table 6.20 lists types of lunar activities and characteristic implementations that can be woven into a strategy.

We describe here a program that would lead to long-term human presence on the Moon. The strategy mixes robotic and human exploration in a manner that might be a template for Mars exploration. In general, robotic systems will be present whenever humans are undertaking exploration and development activities. However, in advance of human exploration missions, substantial progress can be made with purely robotic missions.

Table 6.19. Methods of achieving global access to the Moon.

Approach	***Characteristics***	***Evaluation***
Direct Launch from Earth	Expendable vehicles from Earth; low payload/launch mass	Expensive
Launch from L-1 propellant depot	Reusable landers; Opportunities for repeated missions	Requires 4-times the lander mass in propellant at L-1; Not viable without lunar propellant production
Launch from L-1 propellant depot; Propellant production on Moon both at central facility (to provide propellant to L-1) and individually (to provide propellant to individual landers.	Reusable landers; Expendable propellant production hardware; Propellant production on surface for individual missions; Transport of propellant to L-1 from central lunar production facility	Significant cost reduction after infrastructure established; Surface missions must remain in place until propellant is produced. Propellant production hardware is expendable. Propellant production opportunities differ from place to place on Moon
Reusable lunar hopper, using propellant produced on Moon to move from place to place	Lander carries propellant processing hardware.	Point to point rocket transportation has similar propellant requirements to L-1 to surface transportation; Propellant production opportunities differ from place to place on Moon
Surface transportation system	Electric vehicles with regenerable fuel cells; network of surface fuel cell regeneration systems (photovoltaic arrays).	Energy and mass efficient; Slower than rocket transportation; propellant depots tailored to local resources; Traverses of surface vehicle occupy many points instead of single point accessible to rocket vehicle; Requires high reliability vehicles; benefits from maintenance capability
Railways (Schrunk et al. 1999) or roadways	Vehicles on prepared roadways	More efficient than individual vehicles; easier maintenance; access constrained to infrastructure pathways

A “robotic outpost strategy” is proposed for the early exploration and development of the Moon. The robotic outpost is a strategy advanced by Friedman and Murray (2003) as a means of bridging the apparent gap between the capabilities of current robotic programs, such as those that have investigated the planets, asteroids and comets of the Solar System, and the human exploration missions to Mars, which tend to be two orders of magnitude larger in mass and energy requirements. In the robotic outpost concept for Mars, robotic missions are initially used to reconnoiter landing sites, then deliver instruments to the surface, and subsequently deliver payloads to the surface that prepare for human exploration (such as propellant production plants). In the case of the Moon, the robotic missions could have a more complex role, emplacing much of the infrastructure that is needed to support humans and reducing the cost of human exploration. They would be followed by the establishment of a permanent human outpost that would then grow in capability to support expanded human presence on the Moon. Robotic science missions could be conducted during all phases of the strategy.

Table 6.20. Potential lunar activities.

Lunar Activities	***Characteristics of Implementation***	***Rationale***
Scientific reconnaissance on a global basis, including emplacement of instrument networks	Robotic orbiters, landers, sample return	The absence of compelling urgency implies small per-mission investments; human global access may be too expensive
Detailed investigations of specific sites	Human sorties	Field investigations require intensive, iterative study, but not necessarily permanent facilities
Detailed investigations of hazardous sites	Robotic exploration systems with or without on-site human support	Conditions in areas such as lunar polar craters will be too severe for human access; humans nearby may be effective
Establishment of simple observatories	Robotic emplacement	Observatory systems integrated on Earth require simple site preparation and emplacement processes
Establishment of complex observatories	On-site human supervision; remote operation	Some observatories may require construction or assembly on the Moon; others may require use of local materials
Operation and maintenance of observatories	Human sorties	Observatories will perform better in the absence of humans; maintenance can be done from time to time
Experimental test bed for human mission technology development	Human tended outpost	Deployment, inspection and maintenance by humans requires repeated visits, but not necessarily permanent crew
Determination of long term effects of low gravity on humans and plants	Permanent outpost	Requires immersion of humans in environment
Establishment of materials processing facilities	Robotic emplacement	At scales of early requirements, complex systems could be emplaced and operated by tele-operated robots
Maintenance of complex materials processing facilities	Permanent outpost	Maintenance of chemical and mechanical systems is complex
Environmental studies	Robotic missions; permanent instrument networks	Understanding effects of humans on Moon requires pre-human baseline and monitor system

7.1. Robotic exploration and utilization missions

7.1.1. Reconnaissance orbiter missions. Orbital missions are needed to advance our understanding of the Moon and to help with the selection and verification of human outpost sites. Orbital missions such as Clementine and Lunar Prospector have given us a global view of the Moon. Additional orbital missions will provide improvements to the available data sets. In particular, the following items are important.

Additional global elemental information at higher spatial resolution. The Lunar Prospector (LP) Gamma Ray and Neutron Spectrometer data is limited in resolution due to the non-directional nature of the detector that limits spatial resolution on the surface to approximately the altitude of the spacecraft above the surface. The spatial resolution of LP data was improved by lowering its orbit in the last six months of its mission. Further improvements in the compositional data for the Moon can be obtained by using different detection systems and improving the signal/noise of the measured spectra. This will lead to improved spatial resolution for many elements. The SMART-1 mission includes an X-ray spectrometer with a spatial resolution of about 25 km (Marini et al. 2000). However, the SMART-1 orbit is quite high. An X-ray spectrometer carried in a 100 km orbit could provide maps with resolution of about 1 km. This may be about the highest resolution compositional information that would be useful on the Moon, due to lateral mixing by impacts.

Improved characterization of the lunar polar regions. Although Clementine obtained images of both poles (Nozette et al. 1994), the South Pole was observed during its winter, so that the extent of permanent shadow could not be distinguished from its UVVIS images. Margot et al. (1999) defined permanently shadowed area within 2.5° of the poles, based on radar observations from Earth; however, permanently shadowed areas farther from the poles and on the far side could be depicted by additional Clementine-like imaging, if it were carried out for a full year. Altimetry data for the polar regions is also important scientifically as well as to guide surface activities (Clementine obtained no altimetry southward of 80°S). The prevailing interpretation of hydrogen enrichment at the lunar poles has been that the permanently shadowed areas contain deposits of water-ice. If water-ice is present, its surface and subsurface distribution will be of interest in deciphering the processes by which it has been emplaced. However, the neutron-spectrometer data resolution is not high enough to precisely correlate hydrogen enrichments with permanently shadowed areas. Temperature maps of the lunar polar regions would be very useful. Direct observation of the topography within the shadowed craters and possibly the detection of ice might be accomplished by orbital radar sounding (Nozette et al. 2001) if enough ice is present to provide a useful response. An experiment was performed by crashing the Lunar Prospector at the end of its mission into a crater that could contain ice and looking for evidence of water vapor using terrestrial telescopes, but it detected no water vapor from the impact (Goldstein et al. 1999). Other active surface sensing techniques have been proposed (Meinel et al. 1990), but they have been disregarded in the past because of their high power requirements.

Acquisition of new high-resolution image data. Full global coverage is available at 100 to 200 m resolution from Clementine, generally at high sun angles as the mission's orbit took it over the surface close to local noontime. Some coverage was obtained at 30 m resolution. However, for the far side, there are still rather large errors (~10 km) in knowledge of the absolute location of features (R. Kirk, pers. comm..). As part of a site selection and certification program for a lunar outpost, additional high resolution imaging at 1–2 m resolution would allow detailed outpost-site planning, including positioning of key elements of the outpost.

7.1.2. Robotic surface exploration missions. Robotic surface exploration missions could continue exploration by emplacement of surface geophysical networks, exploration of regions that are difficult to access by humans, and robotic sample returns that could influence the location of a permanent outpost by verifying the existence of a valuable resource.

A global geophysical network of seismic stations. The distributed characteristic of the network and the small size of individual instruments suggest that robotic missions constitute a cost-effective means of emplacing these instruments. They would not provide direct support of lunar development.

Characterization of possible ice deposits in the polar areas. Robotic rovers, capable of conducting traverses in shadow, will be required to document the distribution of ice near the surface. This could be accomplished through traverse geophysical measurements such as ground penetrating radar and active seismic systems, or by a neutron spectrometer with an active neutron source. The three dimensional distribution of ice is a scientific issue, as an ice stratigraphy could record the history of comet impacts on the Moon. To address this issue, a drilling system capable of repeatedly drilling 2–3 m into the surface and bringing subsurface samples for analysis of water and other condensed volatiles would be appropriate.

Outpost site certification. These missions would obtain very high-resolution imaging data for the site and establish physical properties of the regolith at the proposed landing site.

Surface geological investigation and sample collection. These activities can be conducted by robots launched independently from Earth, or by teleoperated robots operated from Earth during a human exploration program. If teleoperated robots are used to collect samples, the samples could be returned to a central lunar outpost for preliminary analysis.

7.1.3. Robotic utilization and infrastructure emplacement missions. A vigorous development program for lunar resource utilization could be carried out robotically. Resource utilization missions are another step upward in complexity from those that would emplace instruments. The utilization missions would typically consist of two distinct elements, a mobile system for accessing local resources, such as an excavator/hauler, and a reaction system that produces the desired resource. Robotic systems could emplace nuclear power supplies, prepare obstacle-free landing sites, and emplace landing beacons. A robotic mission to establish a lunar photovoltaic power system has been defined by Ignatiev et al. (1998).

7.2. First permanent outpost established

The emphasis of this outpost would be on relatively local exploration, development and demonstration of resource utilization technologies, and establishment of technology test beds. Technologies that support self-reliant long-term human habitation, such as regenerable life support systems would be emphasized. Humans would be observed medically and psychologically as the first long term planetary surface missions were undertaken. This could be an essential step toward human migration beyond the Earth-Moon system and is essential if permanent human habitation of the Moon is undertaken. Robotic missions would continue, providing global surface access, sample collection and instrument placement. These systems would be refueled and maintained at the human outpost. The first economic uses of lunar resources would be made during this phase. Scientific laboratories and human-tended observatories would be established. An initial outpost might have facilities for 6–10 people, with tours of duty starting at a few months and extending to 1–2 years, potentially limited by undesirable changes in the human body in long lunar stays.

Scientific exploration by humans during this phase would be concentrated around the landing site, perhaps out to a distance of 20–30 km. Longer range surface traverses could be conducted by robotic systems, bringing back samples from distant sites and conducting reconnaissance surveys for later human expeditions. There are many experiments that could be conducted by humans within these constraints, including:

- A systematic survey and sampling of small impact craters, to establish the nature of impactors and the age distribution of recent craters.
- A deep trench to study the stratigraphy of the lunar surface in detail to a depth of several meters.
- Drilling into the mare regolith to determine the depth to bedrock as well as to penetrate bedrock, looking for contacts between volcanic units and the possibility of fossil regolith layers.
- Sampling complex rock boulders, if present in the selected area.

- Conducting resource extraction experiments to support expanded human lunar presence, economic utilization.
- Learning how to maintain complex equipment on the lunar surface.

In this phase, humans and robots would have global access for science and utilization. Surface transportation would be inexpensive and routine between several regional lunar facilities, with the potential to establish short-term field camps for human scientific and resource exploration. As economic potential develops at a given site, such a short-term field camp might grow into a regional facility. Economic utilization of lunar resources would be the driver for outpost expansion. Tourism could begin. Services provided for people on the Moon and in space would be promoted by lowered transportation costs, based on lunar resources and energy. The size of the main outpost could grow to hundreds or larger, depending on the economic productivity of the outpost, and subsidiary facilities could support groups of people as needed for scientific or commercial activities.

A number of outstanding issues are associated with this exploration strategy, including:

1. What are appropriate locations for permanently occupied outposts? This is a question that can be addressed with the robotic exploration of Phase I and includes considerations of what sites are better for science, resource extraction, and other activities that may be site-dependent.
2. What are the experiments/demonstrations that should be conducted in earlier phases to reduce the risk and mass of subsequent phases? This depends on the long-term objectives adopted for lunar development. Certainly, experiments that allow improvement in lunar operations efficiency and safety would be prominent.
3. What resources are available, and what must be found, if anything, to make the strategy viable? These can be established by early robotic missions, but as in the case of the lunar polar ice question, may require human explorers on site to make final conclusions. Lunar polar ice appears to be the highest priority resource-related issue for near term exploration.
4. What technologies should be developed that would provide the greatest advantage to development strategies? For example, is the development of technology to produce solar cells from lunar material more important than the development of a highly reusable cryogenic H_2/O_2 engine?
5. What is the proper mix of science, exploration and technology development for each phase to maintain program momentum? This is a political question, associated with the source of funding for the program. At current levels of investment in lunar missions, a significant commercial enterprise such as lunar tourism or solar power development could dwarf science and exploration efforts.

In conclusion, the discussion and vision expressed in this chapter could not have been advanced without the forgoing exploration program. In the same manner, discoveries made in carrying out the exploration strategy discussed here will form the basis for new sets of questions and conclusions about the Moon, its origin and history, and its role in the future course of human exploration and utilization of space. The newly-announced NASA emphasis on a renewed lunar program can prove to be a critical step in this progression of humanity from the Earth into the cosmos.

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